PHYSICAL SENSORS FOR ENVIRONMENTAL SIGNALS

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Master Degree in Artificial Intelligence for Science and Technology (AI4ST)

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OUTLINE OF THE COURSE

- Lecture 1: Introduction to environmental signals and physical sensors
- Lab 1: Introduction to instruments for measurements
- Lecture 2: Vibrations: sources and detection
- Lab 2: Characterisation of an acoustic system
- Lecture 3: Distance, position and speed measurement
- Lab 3: Measuring distance with ultrasounds and speed with an accelerometer
- Lecture 4: Electromagnetic radiation: sources and detection
- Lab 4: Detecting and generating light

SENSING THE ENVIRONMENT

SENSING THE ENVIRONMENT

Sources

- Temperature
- Pressure
- Distance and position
- Speed
- Vibrations
- Acoustic
- Radiations: particles & light
- Chemical pollutants

SENSING THE ENVIRONMENT

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POSITION AND DISTANCE

The concept of position

In physics, the concept of position refers to the **location** of an object in space relative to a chosen reference point or **coordinate system**. It is a fundamental quantity used to describe the spatial location of an entity, defined by its distance and direction from the reference point.

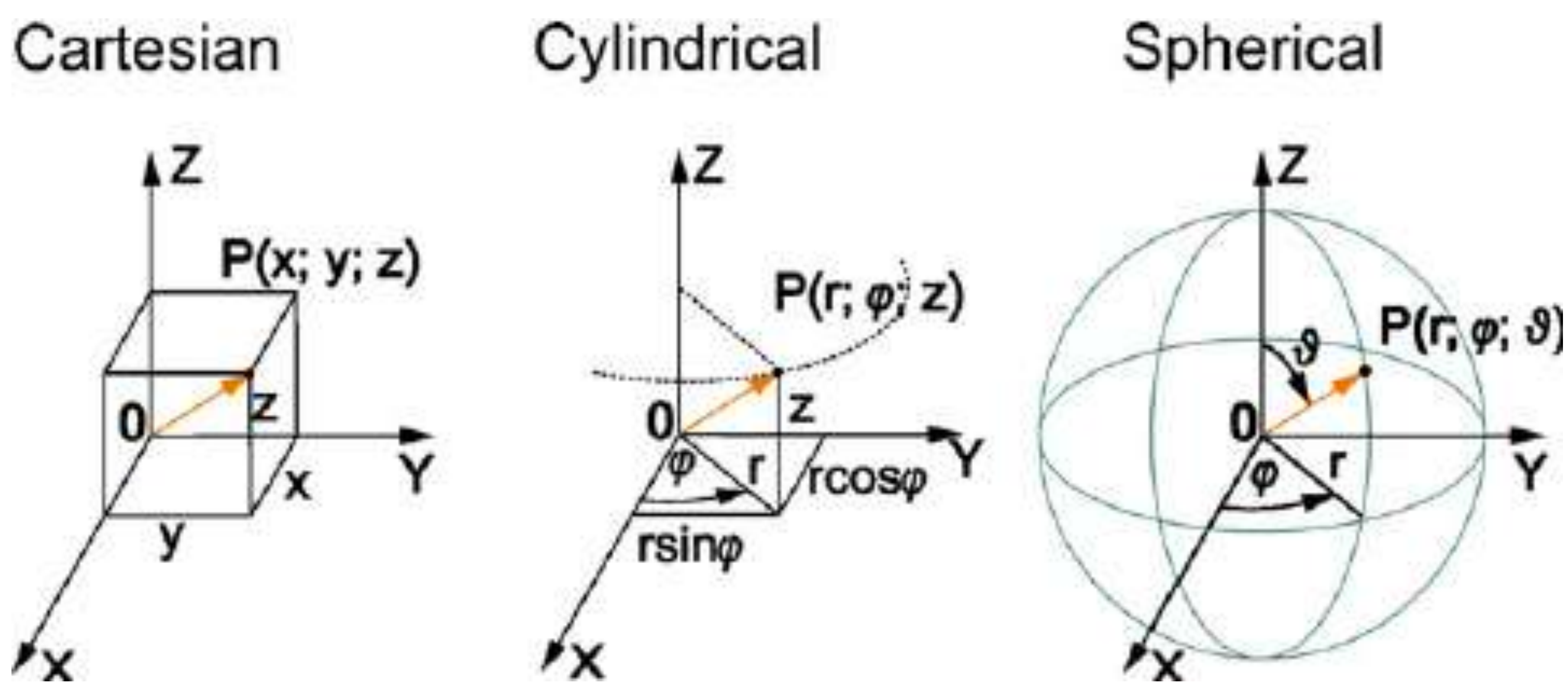
Position is typically described using a set of coordinates in a specific coordinate system, such as Cartesian coordinates (x, y, z) in three-dimensional space or polar coordinates (r, θ) in circular or spherical systems.

The concept of position forms the basis for understanding motion, as changes in position over time result in displacement, velocity, and acceleration, forming the foundation of kinematics and dynamics in physics.

It allows scientists to precisely describe the spatial arrangement of objects, particles, or systems within a defined space, essential for analyzing physical phenomena across various scientific disciplines.

POSITION AND DISTANCE

The concept of position: coordinate systems



POSITION AND DISTANCE

The concept of position: coordinate systems

Coordinate Transformation Formula Sheet

Table with the Del operator in rectangular, cylindrical, and spherical coordinates			
Operation	**Cartesian coordinates (x,y,z)**	**Cylindrical coordinates (ρ,φ,z)**	**Spherical coordinates (r,θ, φ)**
Definition of coordinates	$\rho = \sqrt{x^2+y^2}$, $\phi = \arctan(y/x)$, $z = z$	$x = \rho\cos\phi$, $y = \rho\sin\phi$, $z = z$	$x = r\sin\theta\cos\phi$, $y = r\sin\theta\sin\phi$, $z = r\cos\theta$
	$r = \sqrt{x^2+y^2+z^2}$, $\theta = \arctan\left(\frac{\sqrt{x^2+y^2}}{z}\right)$, $\phi = \arctan(y/x)$	$r = \sqrt{\rho^2+z^2}$, $\theta = \arctan(\rho/z)$, $\phi = \phi$	$\rho = r\sin(\theta)$, $\phi = \phi$, $z = r\cos(\theta)$
Definition of unit vectors	$\hat{\boldsymbol{\rho}} = \cos\phi\hat{\mathbf{x}} + \sin\phi\hat{\mathbf{y}}$, $\hat{\boldsymbol{\phi}} = -\sin\phi\hat{\mathbf{x}} + \cos\phi\hat{\mathbf{y}}$, $\hat{\mathbf{z}} = \hat{\mathbf{z}}$	$\hat{\mathbf{x}} = \cos\phi\hat{\boldsymbol{\rho}} - \sin\phi\hat{\boldsymbol{\phi}}$, $\hat{\mathbf{y}} = \sin\phi\hat{\boldsymbol{\rho}} + \cos\phi\hat{\boldsymbol{\phi}}$, $\hat{\mathbf{z}} = \hat{\mathbf{z}}$	$\hat{\mathbf{x}} = \sin\theta\cos\phi\hat{\mathbf{r}} + \cos\theta\cos\phi\hat{\boldsymbol{\theta}} - \sin\phi\hat{\boldsymbol{\phi}}$, $\hat{\mathbf{y}} = \sin\theta\sin\phi\hat{\mathbf{r}} + \cos\theta\sin\phi\hat{\boldsymbol{\theta}} + \cos\phi\hat{\boldsymbol{\phi}}$, $\hat{\mathbf{z}} = \cos\theta\hat{\mathbf{r}} - \sin\theta\hat{\boldsymbol{\theta}}$
	$\hat{\mathbf{r}} = \sin\theta\cos\phi\hat{\mathbf{x}} + \sin\theta\sin\phi\hat{\mathbf{y}} + \cos\theta\hat{\mathbf{z}}$, $\hat{\boldsymbol{\theta}} = \cos\theta\cos\phi\hat{\mathbf{x}} + \cos\theta\sin\phi\hat{\mathbf{y}} - \sin\theta\hat{\mathbf{z}}$, $\hat{\boldsymbol{\phi}} = -\sin\phi\hat{\mathbf{x}} + \cos\phi\hat{\mathbf{y}}$	$\hat{\mathbf{r}} = \sin\theta\hat{\boldsymbol{\rho}} + \cos\theta\hat{\mathbf{z}}$, $\hat{\boldsymbol{\theta}} = \cos\theta\hat{\boldsymbol{\rho}} - \sin\theta\hat{\mathbf{z}}$, $\hat{\boldsymbol{\phi}} = \hat{\boldsymbol{\phi}}$	$\hat{\boldsymbol{\rho}} = \sin\theta\hat{\mathbf{r}} + \cos\theta\hat{\boldsymbol{\theta}}$, $\hat{\boldsymbol{\phi}} = \hat{\boldsymbol{\phi}}$, $\hat{\mathbf{z}} = \cos\theta\hat{\mathbf{r}} - \sin\theta\hat{\boldsymbol{\theta}}$

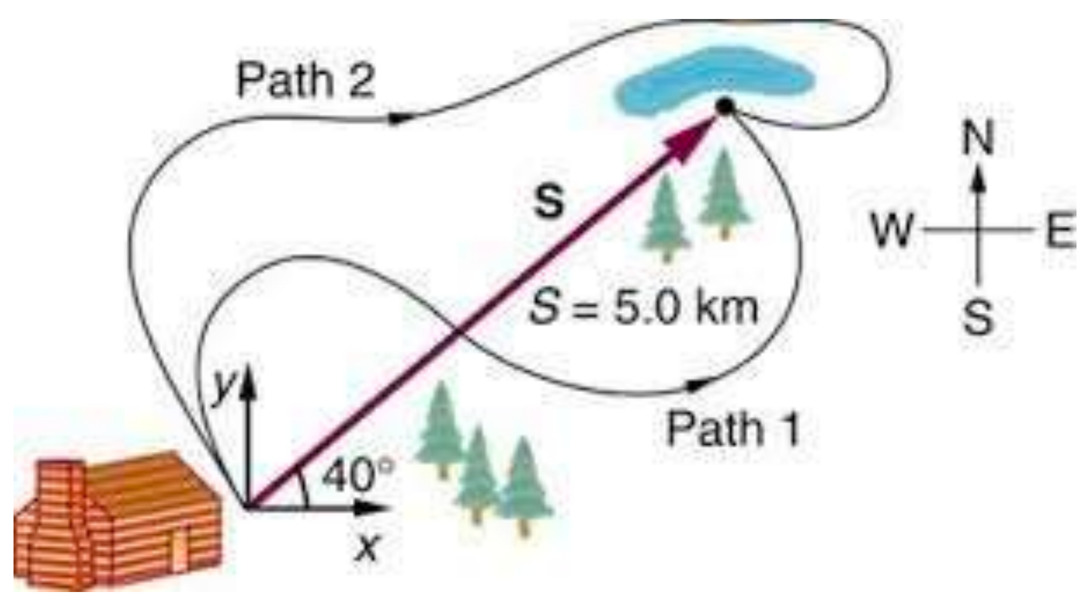
POSITION AND DISTANCE

The concept of distance

Distance is a fundamental concept used to quantify spatial relationships. It is a quantitative measure of the separation between two points in space, representing the length of the shortest path connecting them.

It does not take into consideration the direction between the two points it measures; hence, it is a **scalar quantity**. This therefore means that distance has only magnitude but no direction.

Accurate distance measurement relies on precise tools and methodologies tailored to specific contexts. It s vital for scientific experiments, navigation, mapping, and the analysis of spatial relationships within complex systems.



POSITION AND DISTANCE

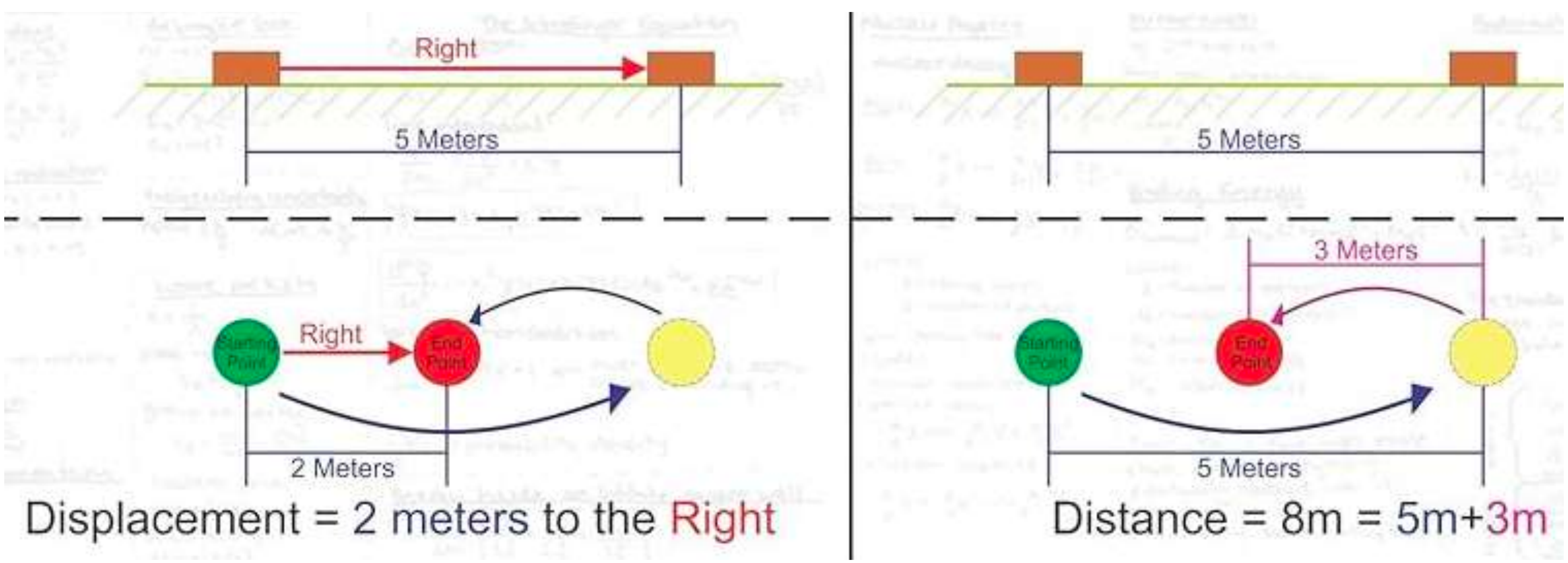
Displacement and distinction with distance

In physics, displacement is defined as the distance travelled or moved in a specific direction.

It is a **vector quantity** that considers both the magnitude and the direction of the change in position.

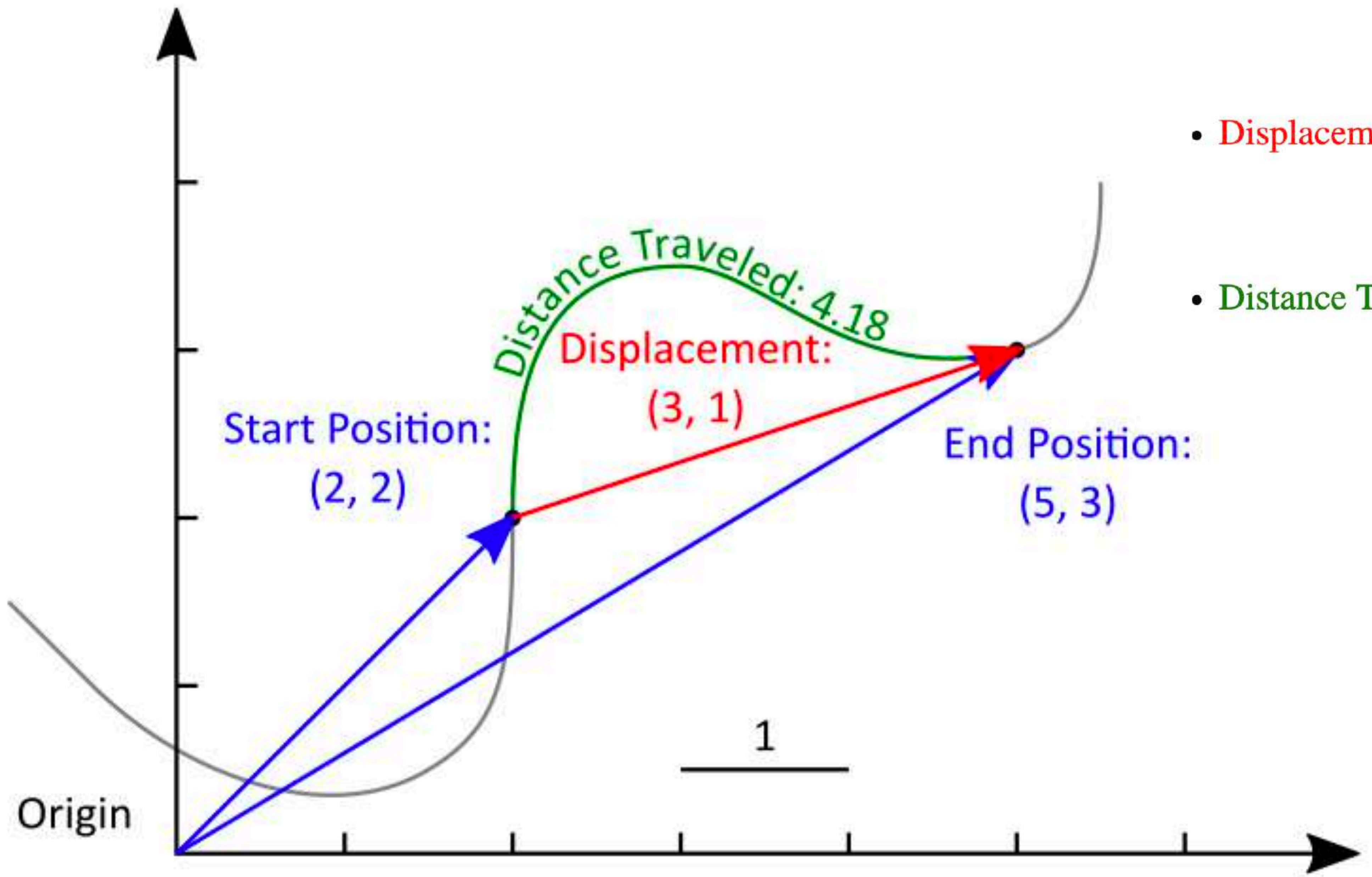
Displacement differs from distance, as it specifically accounts for the net change in location rather than the total path traveled.

Calculating displacement involves understanding the initial and final positions of an object within a coordinate system, often represented using vectors in two or three dimensions.



https://stoplearn.com/position-distance-and-displacement/

POSITION AND DISTANCE



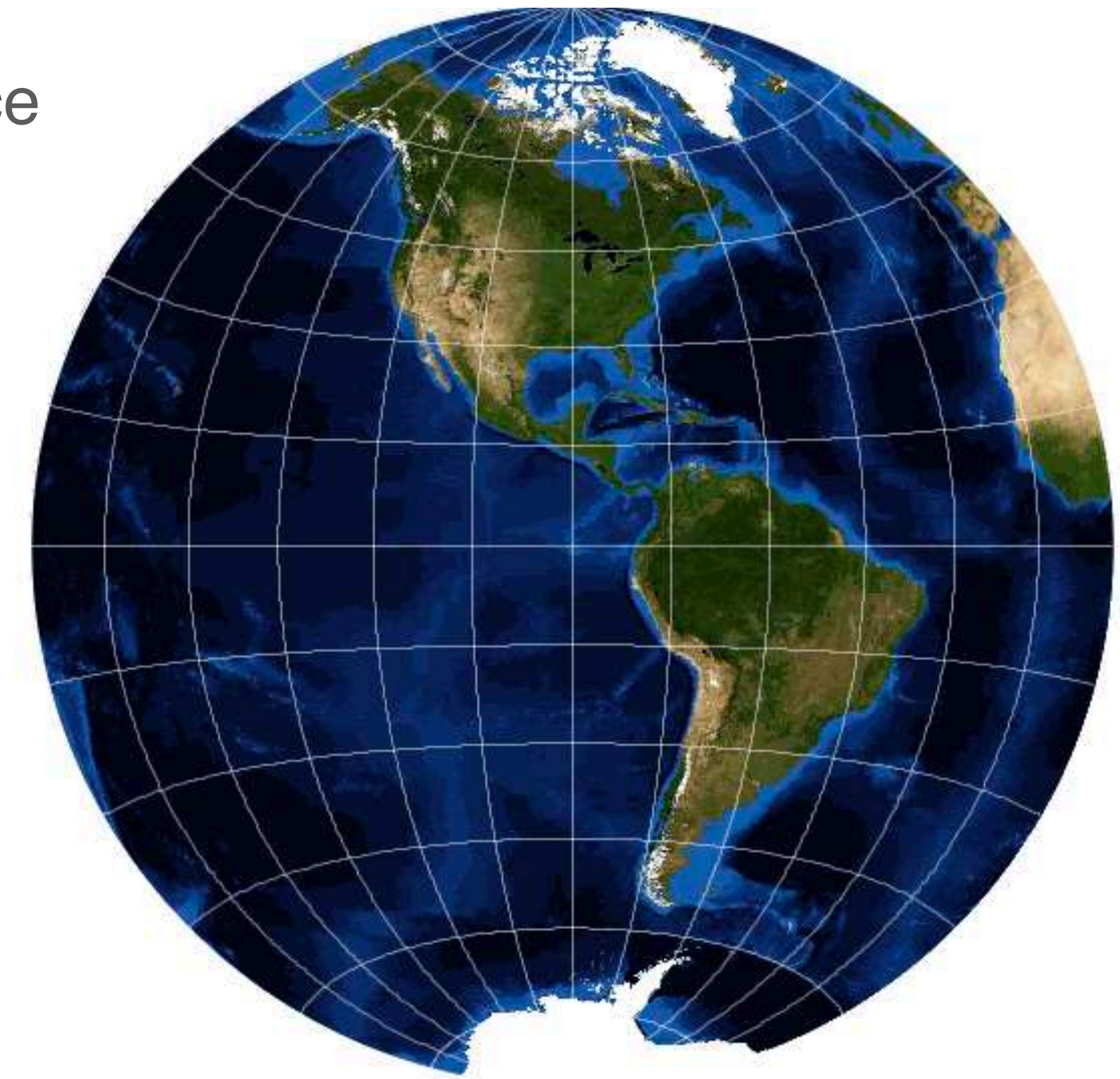
- Position: $\vec{p}(t)$
- Displacement†: $\vec{p}(t_2) - \vec{p}(t_1)$
- Distance Traveled: $\int_{t_1}^{t_2} \left\| \frac{d\vec{p}(t)}{dt} \right\| dt$

POSITION MEASUREMENT ON EARTH

Spatial reference system (**SRS**) or **coordinate reference system** (**CRS**)

It is a framework used to precisely measure and reference spatial locations on the surface of Earth as coordinates. It is thus the application of the abstract mathematics of coordinate systems and analytic geometry to geographic space.

A CRS typically comprises axes or grids, allowing the identification of positions using numerical values along specific dimensions. Common examples include Cartesian coordinates (x, y, z) in three-dimensional space or geographic coordinates (latitude, longitude, altitude) on the Earth's surface.



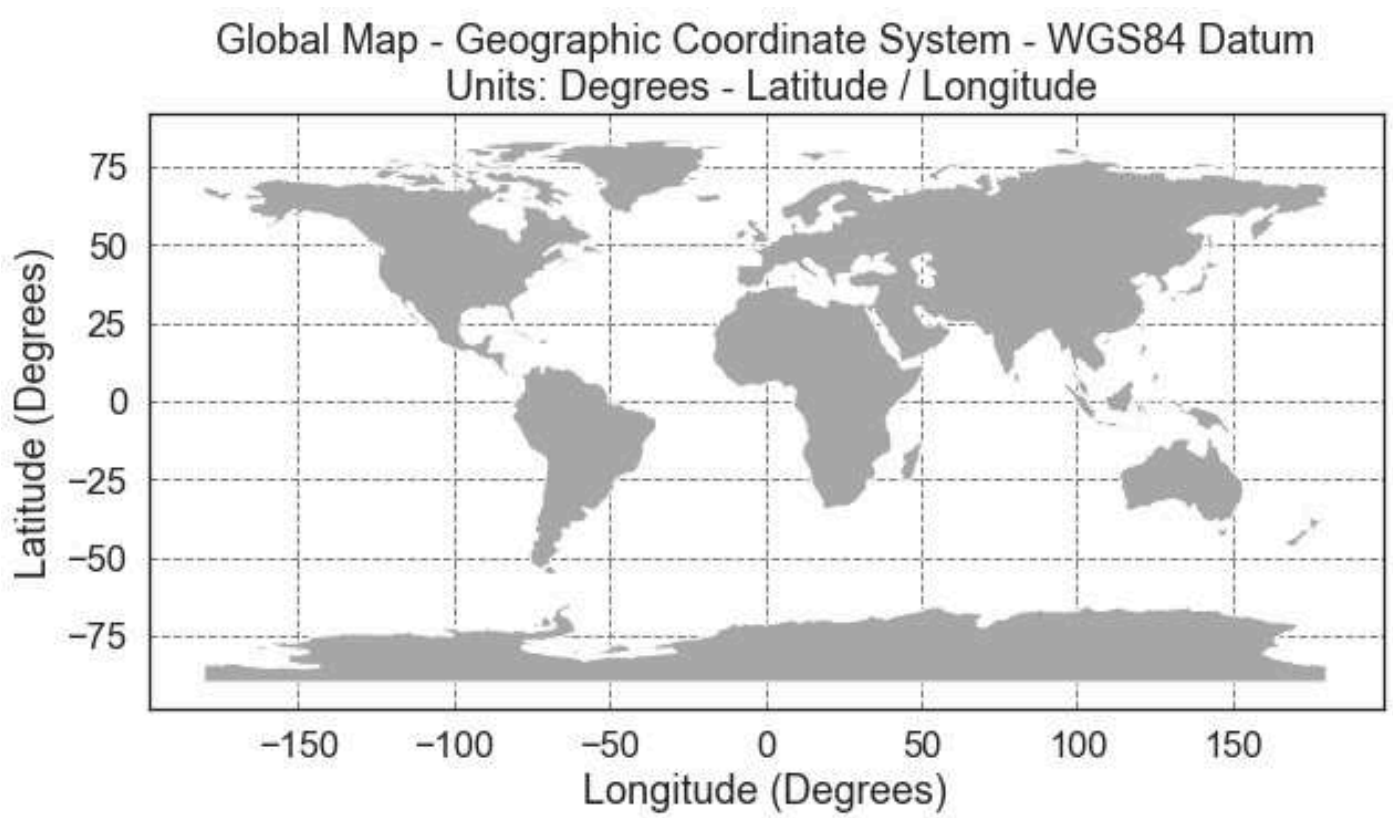
POSITION MEASUREMENT ON EARTH

Spatial reference system (**SRS**) or **coordinate reference system** (**CRS**)

CRSs help standardise the representation of locations across different disciplines and applications, including cartography, geographic information systems, surveying, remote sensing, and civil engineering.

The CRS have undergone a standardisation in international specification, such as the *EPSG code* and *ISO 19111:2019* Geographic information, also published by the *Open Geospatial Consortium (OGC).*

The SRS systems can be global (like the World Geodetic System, WGS84) or local, tailored to specific regions or projects.



EPSG GEODETIC PARAMETER DATASET Managed by IOGP's Geomatics Committee

Open Geospatial Consortium

https://epsg.org/home.html https://www.ogc.org/

https://www.iso.org/committee/54904.html

POSITION MEASUREMENT ON EARTH

Spatial reference system (**SRS**) or **coordinate reference system** (**CRS**)

Any coordinate reference system definition is composed of several specifications:

- **Coordinate system**, an abstract framework for measuring locations. Its definition consists of a measurable space (whether a plane, a three-dimension void, or the surface of an object such as the Earth), an origin point, a set of axis vectors emanating from the origin, and a unit of measure.

- **Geodesic horizontal datum**, which binds the abstract coordinate system to the real space of the Earth. A horizontal datum can be defined as a precise reference framework for measuring geographic coordinates (latitude and longitude). Examples include the World Geodetic System and the 1927 and 1983 North American Datum. A datum generally consists of an estimate of the shape of the Earth (usually an ellipsoid), and one or more anchor points or control points, established locations (often marked by physical monuments) for which the measurement is documented.

- **Choice of map projection**, to convert the spherical coordinates specified by the datum into cartesian coordinates on a planar surface.

https://anythingmapping.com/2021/10/21/why-do-coordinate-systems-matter/

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- **Choice of map projection**, to convert the spherical coordinates specified by the datum into cartesian coordinates on a planar surface.

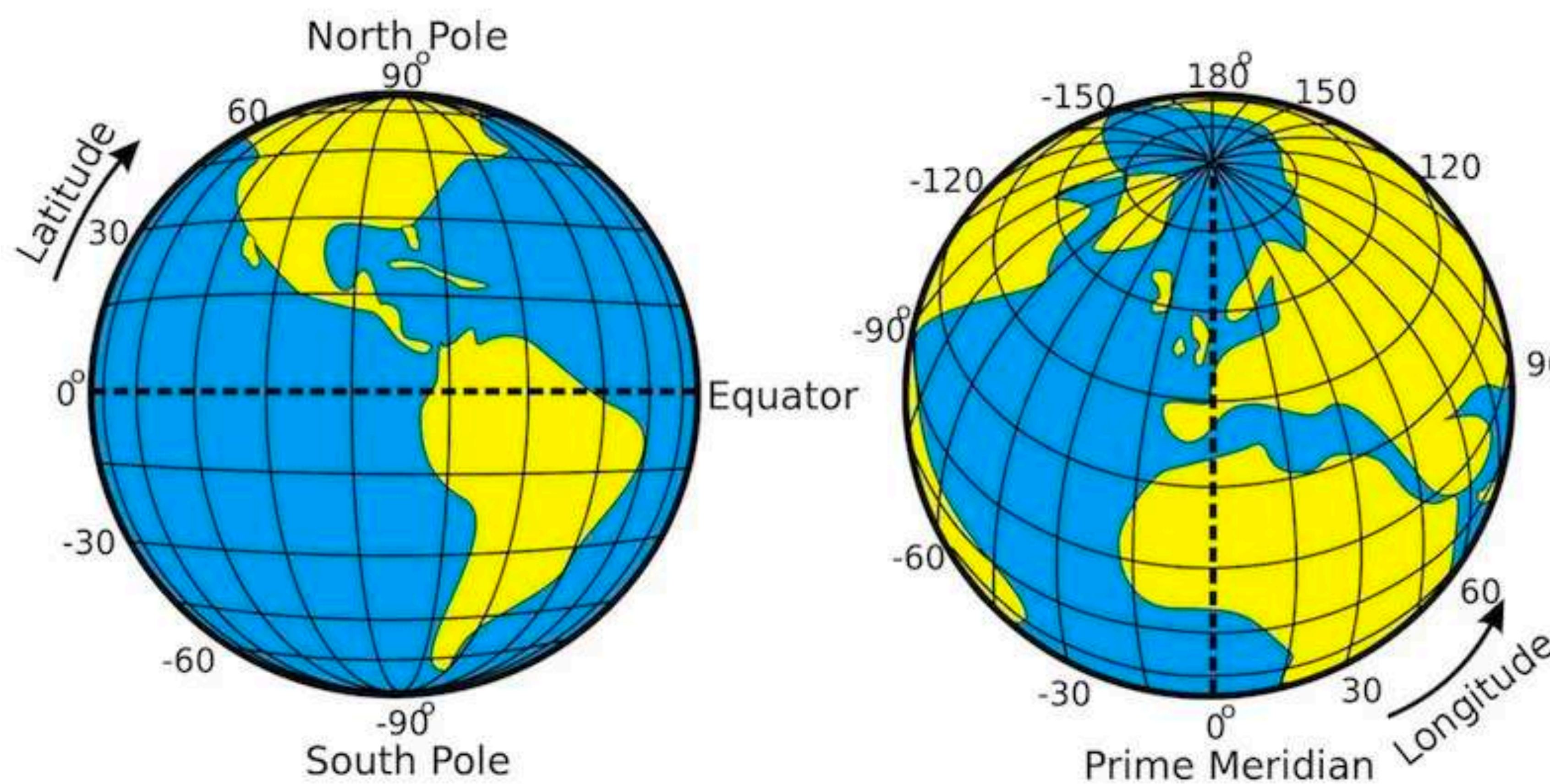
POSITION MEASUREMENT ON EARTH

Spatial reference system (SRS): coordinate system

Strategies for the definition of the spatial reference coordinate systems, according to the EPSG, ISO, and OGC standards:

1. *Geographic coordinate system (or geodetic) [GCS]*

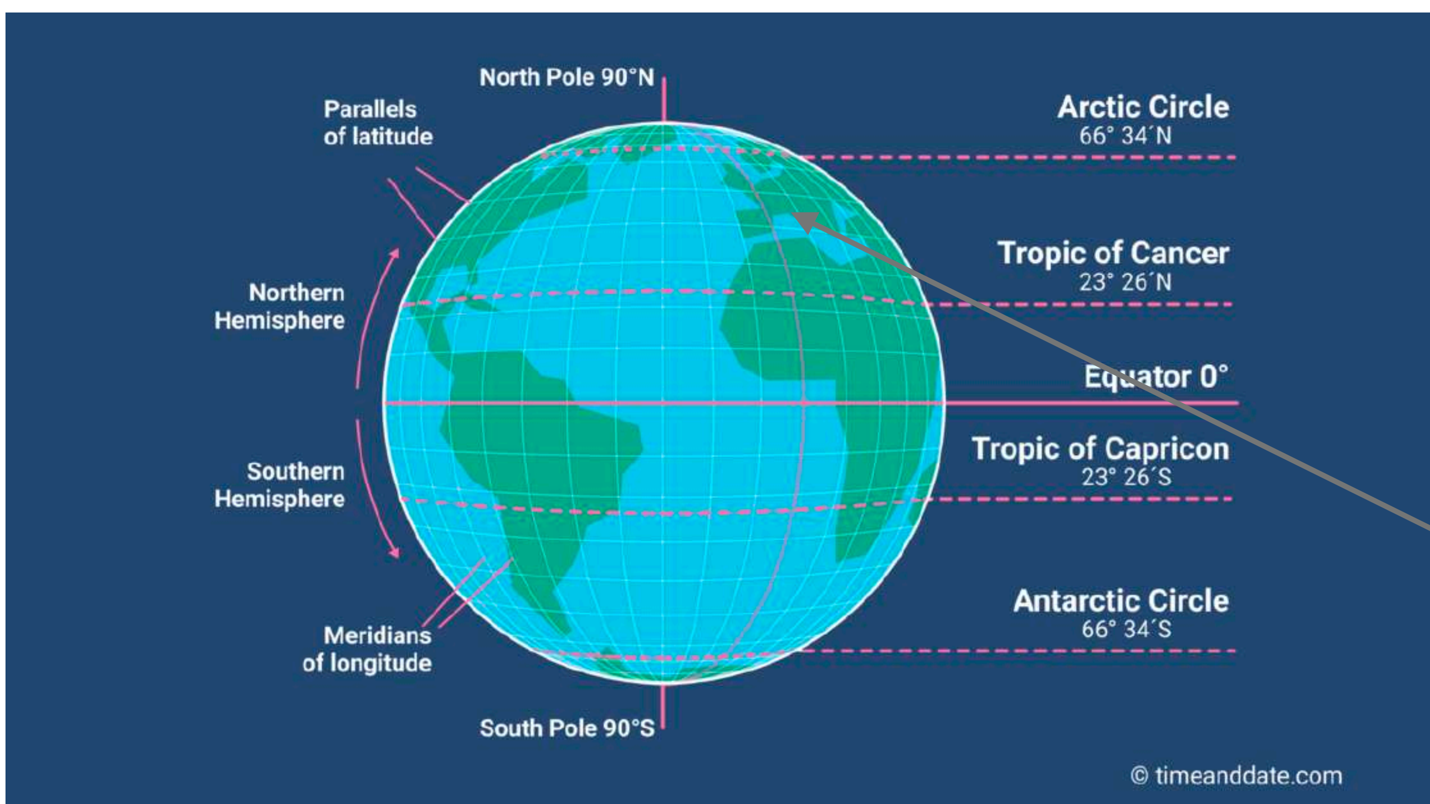
Spherical coordinate system measuring locations directly on the Earth (sphere or ellipsoid) using **latitude** (degrees north or south of the equator) and **longitude** (degrees west or east of a prime meridian).



POSITION MEASUREMENT ON EARTH

Geographic coordinate system: latitude and longitude

Latitude lines, also known as parallels, run east-west and measure distances north or south of the equator, which is marked at 0 degrees latitude. These lines range from 0° at the equator to a maximum of 90° at the poles (90° N at the North Pole and 90° S at the South Pole). Longitude lines, called meridians, extend from the North Pole to the South Pole and measure distances east or west of the Prime Meridian, which is set at 0° longitude. Longitude values range from 0° to 180° E or W of the Prime Meridian, with 180° both east and west being the same line, forming a complete circle around the Earth



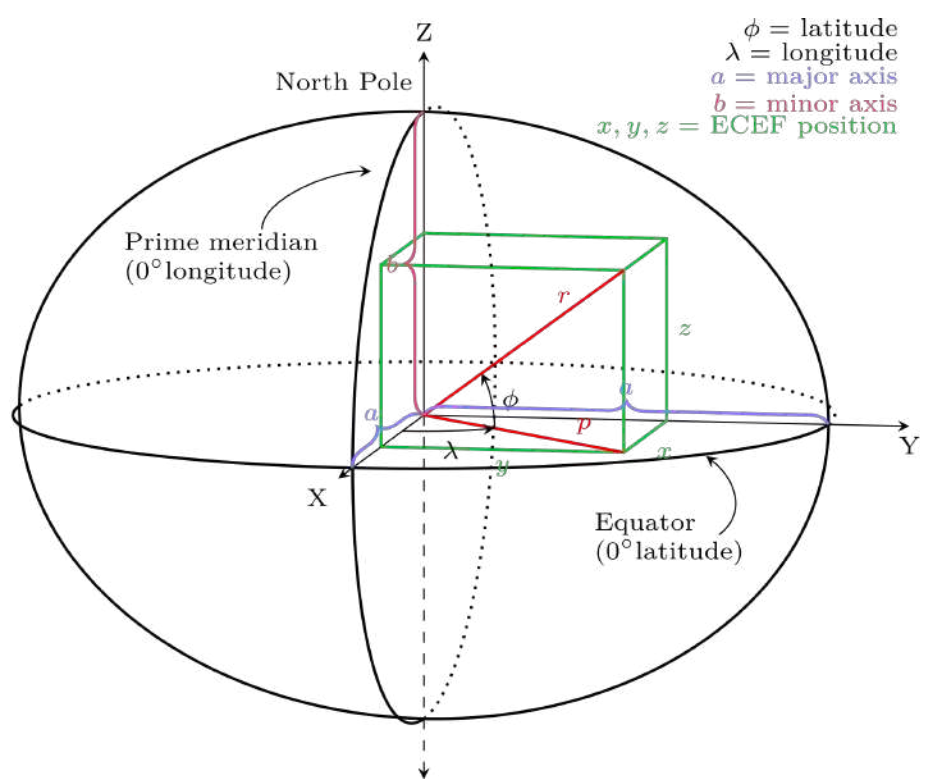
POSITION MEASUREMENT ON EARTH

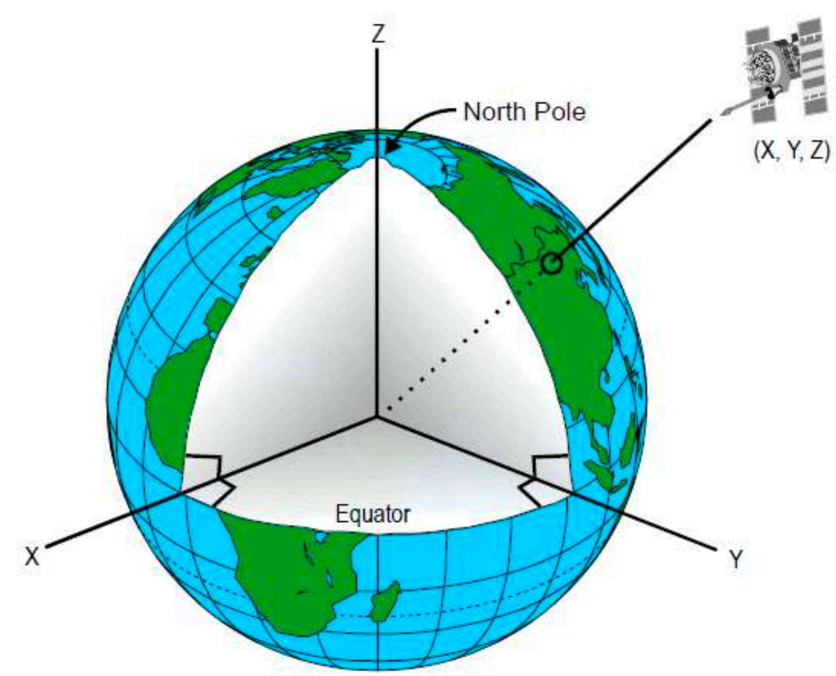
Spatial reference system (SRS): coordinate system

Strategies for the definition of the spatial reference coordinate systems, according to the EPSG, ISO, and OGC standards:

2. *Geocentric coordinate system (or Earth-centered Earth-fixed)*

Three-dimensional **cartesian coordinate system** that models the Earth as a three-dimensional object, measuring locations from a center point, usually the center of mass of the Earth, along X, Y, and Z axes aligned with the equator and the prime meridian. This system is commonly used to track the orbits of satellites, because they are based on the center of mass. *This is the internal coordinate system used by Satellite navigation systems such as GPS* to compute locations using multilateration.





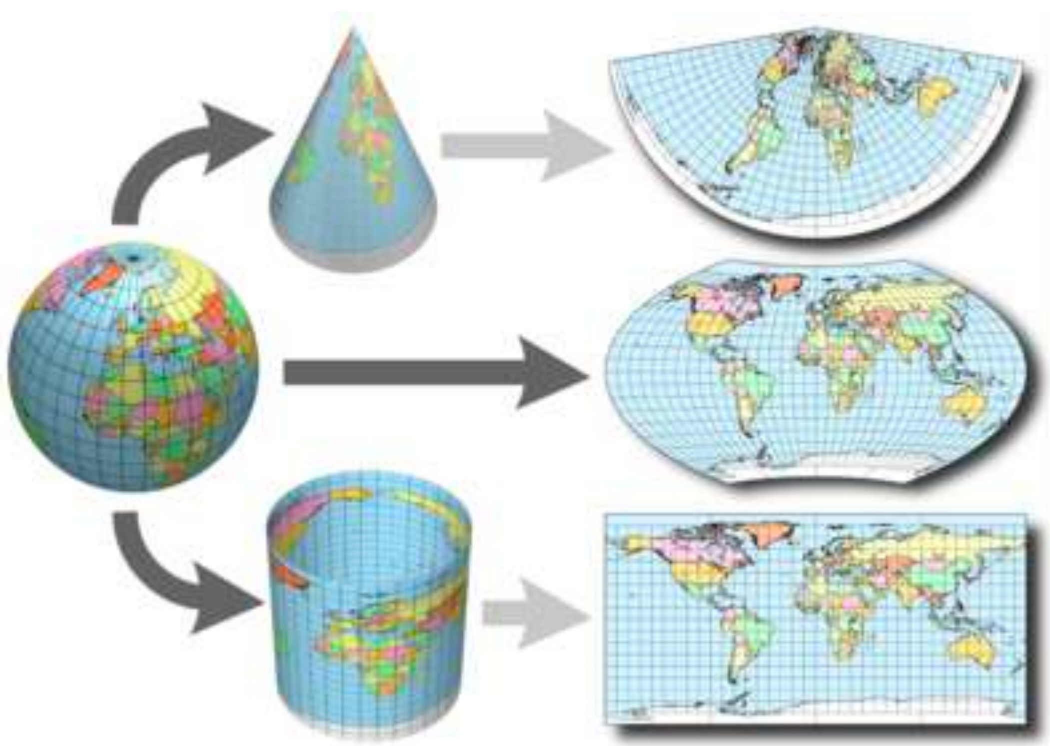
POSITION MEASUREMENT ON EARTH

Spatial reference system (SRS): coordinate system

Strategies for the definition of the spatial reference coordinate systems, according to the EPSG, ISO, and OGC standards:

3. *Projected coordinate system (or planar, grid) [PCS]*

A standardised **cartesian coordinate system** that models the Earth (or a large region thereof) as a plane, measuring locations from an arbitrary origin point along x and y axes more or less aligned with the cardinal directions. Each of these systems is based on a particular Map projection to **create a planar surface from the curved Earth surface**. These are generally defined and used strategically to minimise the distortions inherent to projections.

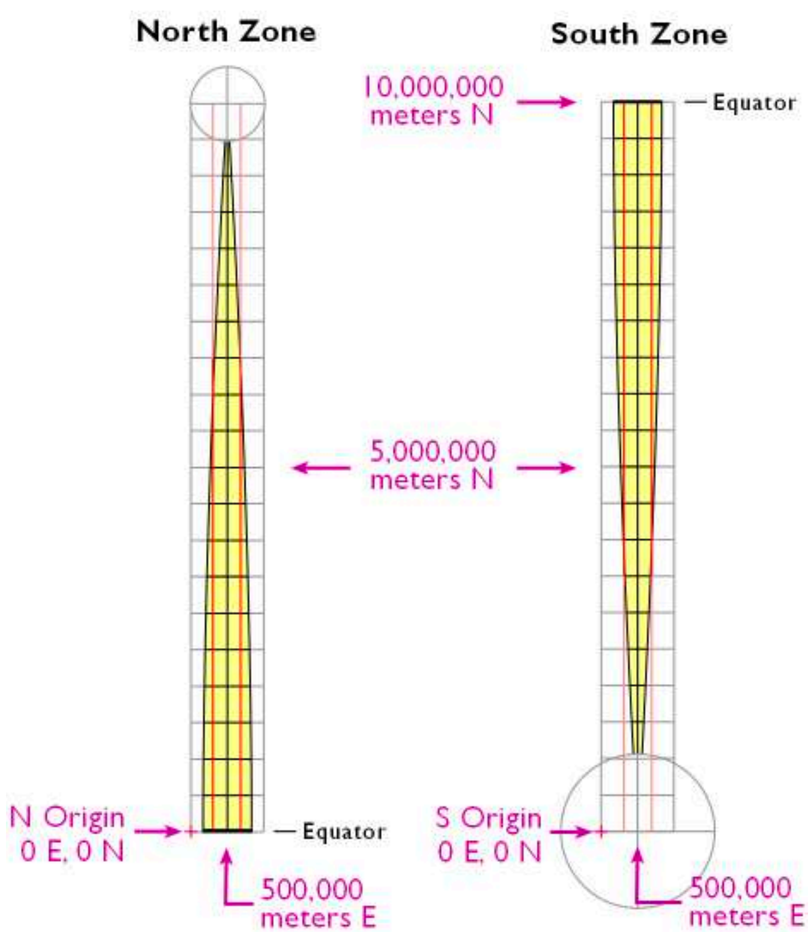


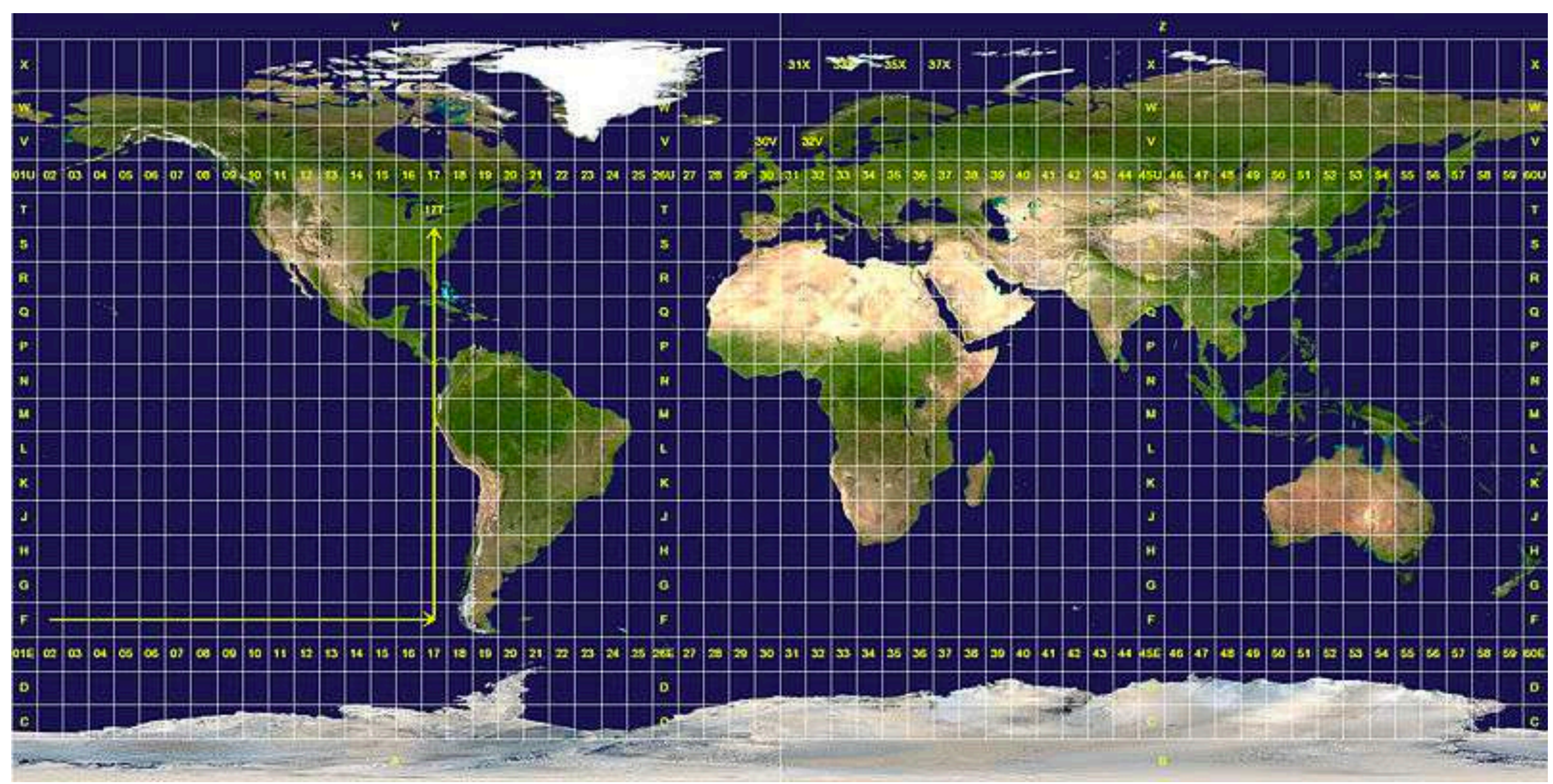
Common examples include the *Universal transverse mercator (UTM)* and national systems such as the British National Grid, and State Plane Coordinate System (SPCS).

POSITION MEASUREMENT ON EARTH

Projected coordinate system: the Universal transverse mercator (UTM)

The UTM is a commonly used projected coordinate reference system. UTM subdivides the globe into zones, numbered 0-60 (equivalent to longitude) and regions (north and south). While UTM zones span the entire globe, UTM uses a regional projection and associated coordinate system. The coordinate system grid for each zone is projected individually using the **Mercator projection**. The origin (0,0) for each UTM zone and associated region is located at the intersection of the equator and a location, 500,000 meters east of the central meridian of each zone. The origin location is placed outside of the boundary of the UTM zone, to avoid negative Easting numbers.





Source: NASA Earth Observatory

POSITION MEASUREMENT ON EARTH

Spatial reference system (SRS): coordinate system

Strategies for the definition of the spatial reference coordinate systems, according to the EPSG, ISO, and OGC standards:

4. *Engineering coordinate system (or local, custom)*

A cartesian coordinate system (2-D or 3-D) that is created for a small area over which the curvature of the Earth can be safely approximated as flat without significant distortion. Locations are typically measured directly from an arbitrary origin point using surveying techniques. These may or may not be aligned with a standard projected coordinate system. Local tangent plane coordinates are a type of local coordinate system used in aviation and marine vehicles.

POSITION MEASUREMENT ON EARTH

Spatial reference system (**SRS**) or **coordinate reference system** (**CRS**)

Any coordinate reference system definition is composed of several specifications:

- **Coordinate system**, an abstract framework for measuring locations. Its definition consists of a measurable space (whether a plane, a three-dimension void, or the surface of an object such as the Earth), an origin point, a set of axis vectors emanating from the origin, and a unit of measure.

- **Geodetic horizontal datum**, which binds the abstract coordinate system to the real space of the Earth. A horizontal datum can be defined as a precise reference framework for measuring geographic coordinates (latitude and longitude). Examples include the World Geodetic System and the 1927 and 1983 North American Datum. A datum generally consists of an estimate of the shape of the Earth (usually an ellipsoid), and one or more anchor points or control points, established locations (often marked by physical monuments) for which the measurement is documented.

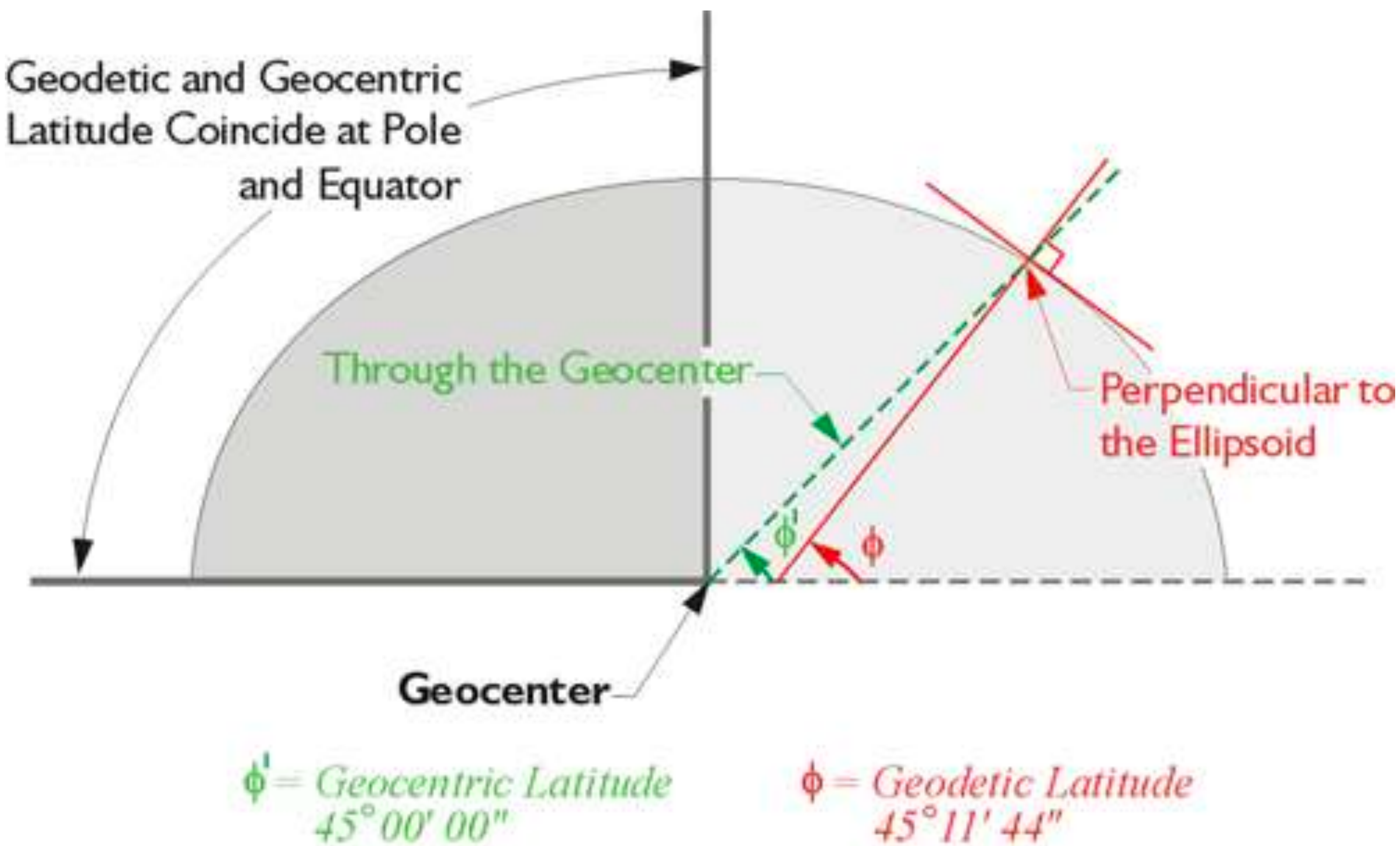
- **Choice of map projection**, to convert the spherical coordinates specified by the datum into cartesian coordinates on a planar surface.

POSITION MEASUREMENT ON EARTH

Spatial reference system (SRS): geodetic datum

A geodetic datum or geodetic system is a global reference frame for precisely representing the position of locations on Earth or other planetary bodies by means of **geodetic coordinates**.

A horizontal datum is used to measure a location across the Earth's surface, in latitude and longitude or another coordinate system; a vertical datum is used to measure the elevation or depth relative to a standard origin, such as mean sea level (MSL).



POSITION MEASUREMENT ON EARTH

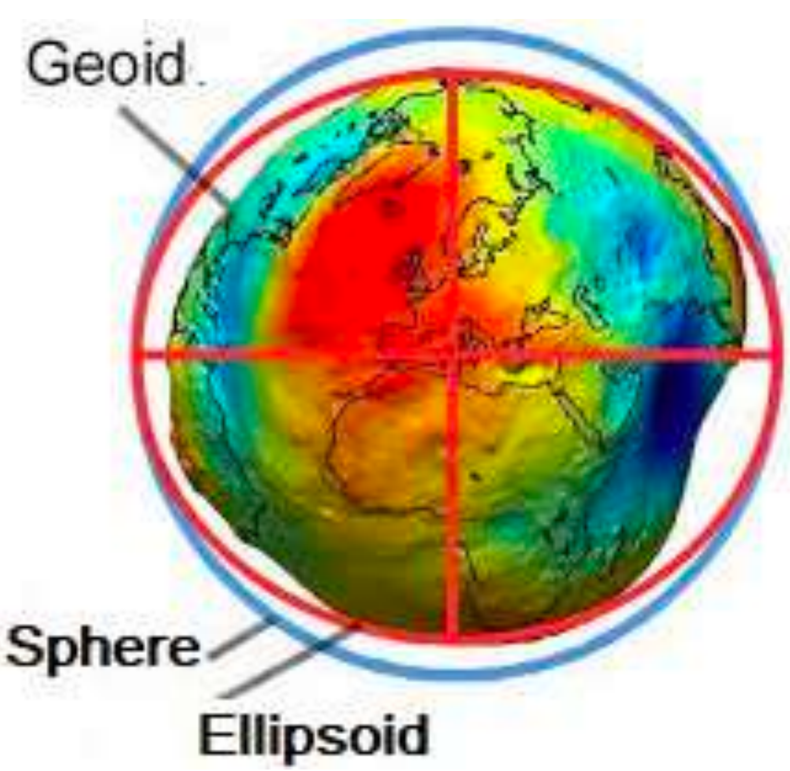
Spatial reference system (SRS): geodetic datum

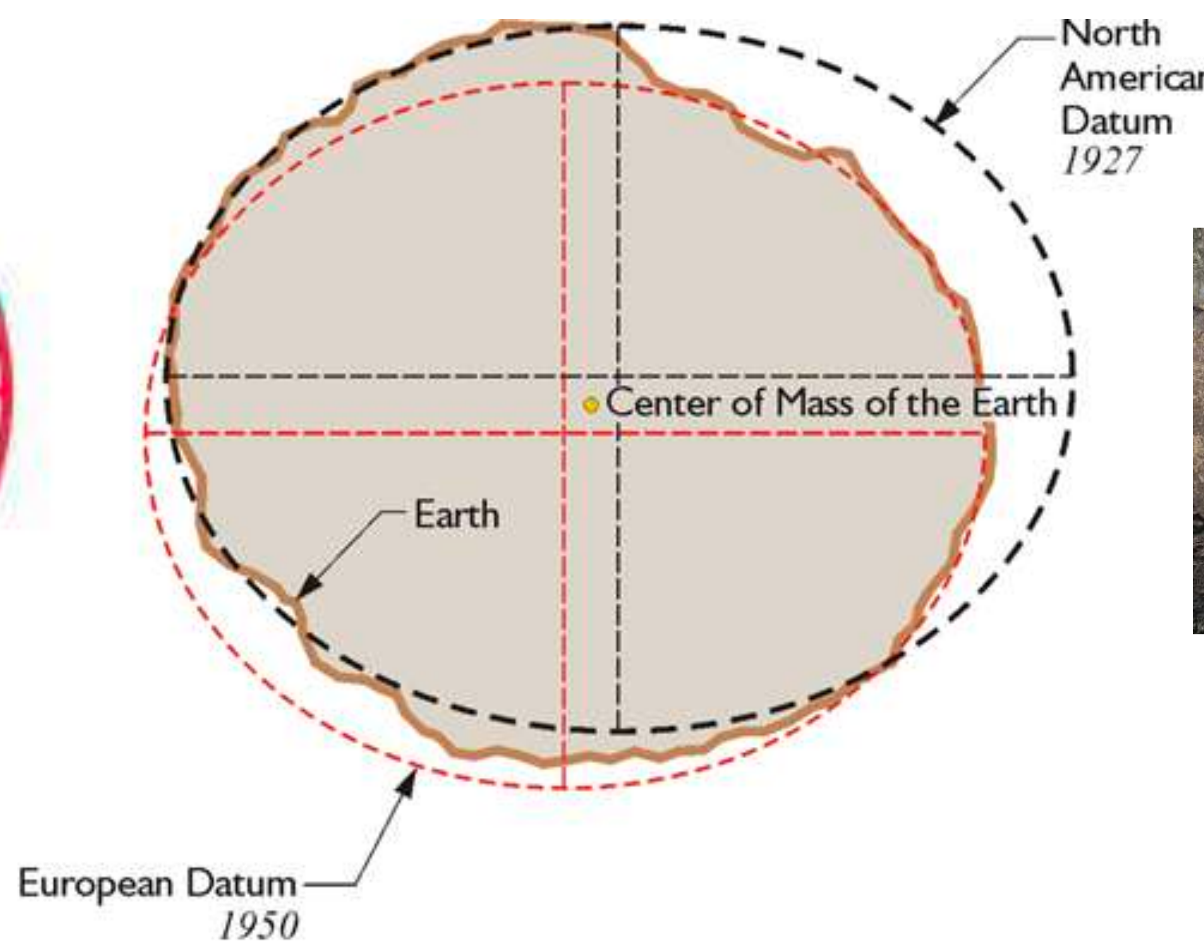
A standard datum specification (whether horizontal or vertical) consists of several parts:

- Model for Earth's shape and dimensions, such as a reference ellipsoid or a geoid;

- Origin at which the ellipsoid/geoid is tied to a known (often monumented) location on or inside Earth

- Multiple control points that have been precisely measured from the origin and monumented

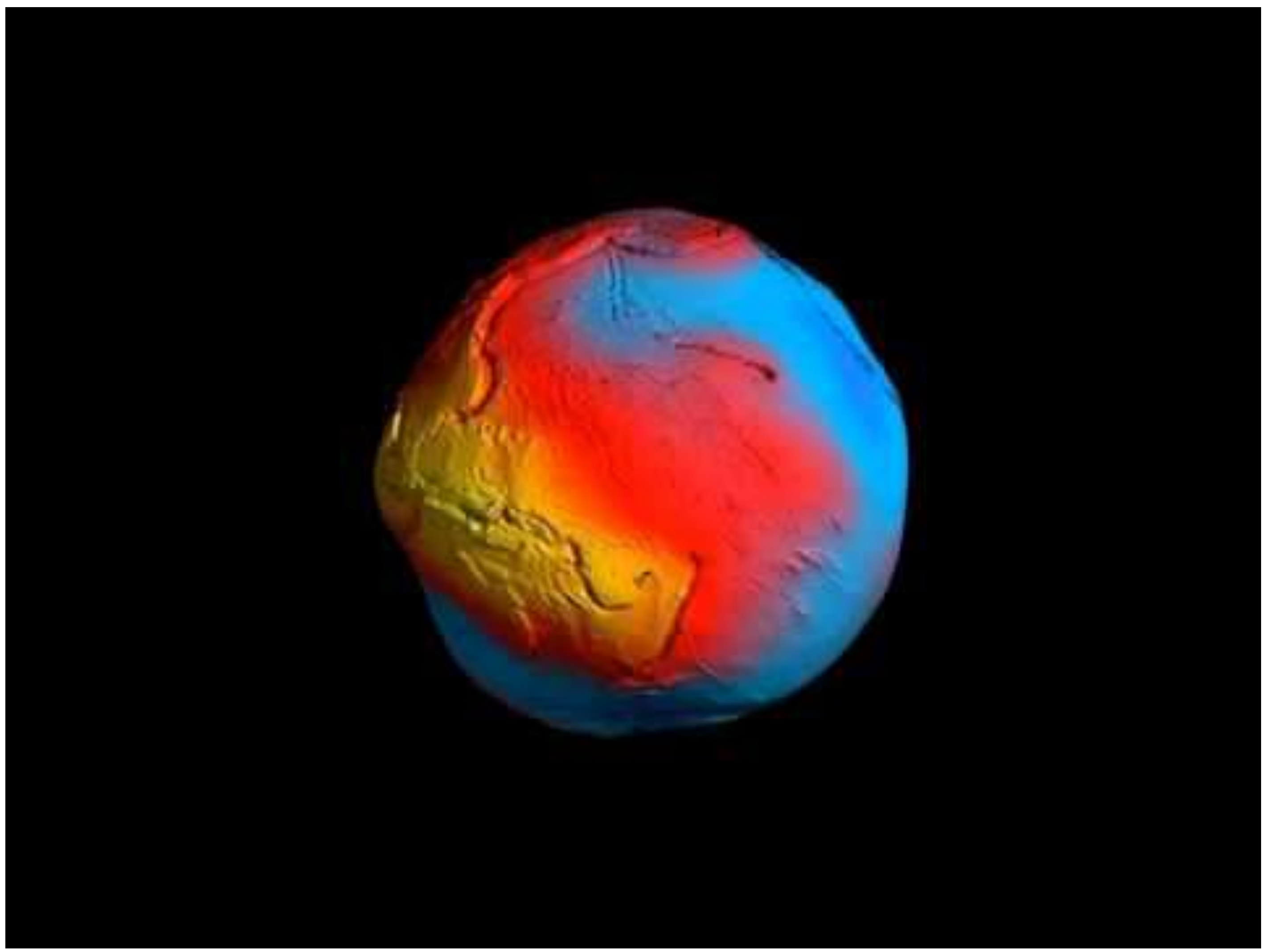




POSITION MEASUREMENT ON EARTH

Spatial reference system (SRS): geodetic datum

Model for Earth's shape and dimensions



https://www.esa.int/ESA_Multimedia/Images/2010/04/Earth_Explorers_The_Earth_s_true_shape

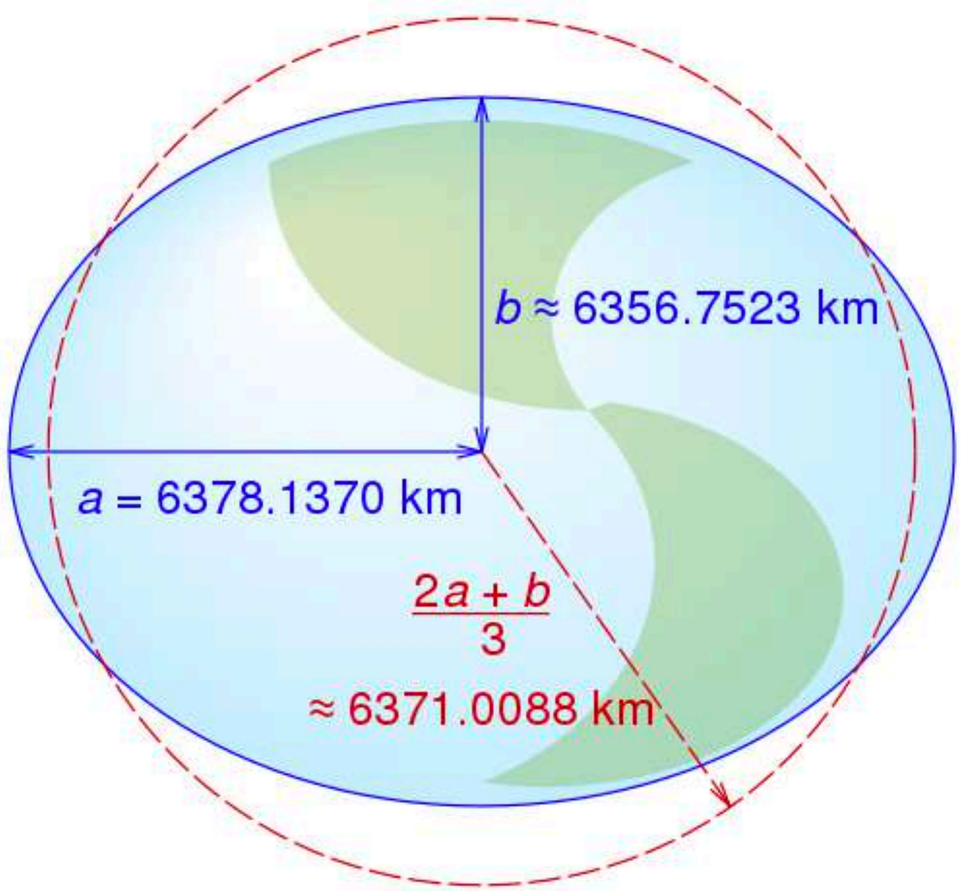
https://blogs.scientificamerican.com/observations/the-geoid-why-a-map-of-earths-gravity-yields-a-potato-shaped-planet/

POSITION MEASUREMENT ON EARTH

Spatial reference system (SRS): geodetic horizontal datum

The World Geodetic System (WGS) is a standard used in cartography, geodesy, and satellite navigation including GPS.

The current version, **WGS 84**, defines an Earth-centered, Earth-fixed coordinate system and a geodetic datum, and also describes the associated Earth Gravitational Model (EGM) and World Magnetic Model (WMM).



Developed by the United States Department of Defense, WGS84 serves as the foundation for global positioning systems (GPS) and geospatial data exchange worldwide.

https://earth-info.nga.mil/?dir=wgs84&action=wgs84

POSITION MEASUREMENT ON EARTH

Spatial reference system (**SRS**) or **coordinate reference system** (**CRS**): examples

EPSG Code	Name	Ellipsoid	Horizontal Datum	CS Type	Projection	Origin	Axes	Unit of Measure
4326	GCS WGS 84	GRS 80	WGS 84	ellipsoidal (lat, lon)	N/A	equator/prime meridian	equator, prime meridian	degree of arc
26717	UTM Zone 17N NAD 27	Clarke 1866	NAD 27	cartesian (x,y)	Transverse Mercator: central meridian 81°W, scaled 0.9996	500km west of (81°W, 0°N)	equator, 81°W meridian	meter
6576	SPCS Tennessee Zone NAD 83 (2011) ftUS	GRS 80	NAD 83 (2011 epoch)	cartesian (x,y)	Lambert Conformal Conic: center 86°W, 34°20'N, standard parallels 35°15'N, 36°25'N	600km grid west of center point	grid east at center point, 86°W meridian	US survey foot

DISTANCE MEASUREMENT

The concept of distance

Distance measurement encompasses a range of methodologies designed to quantify spatial separation with precision and accuracy across diverse applications.

- ***Standard rulers***

Traditional terrestrial methods utilize tools like rulers, tape measures, and surveying instruments such as theodolites and total stations for short to moderate distances. Range mm - m

- ***Time measurement***

Send a signal from one end of the length (interrogating pulse) to be detected to the other, and back again.

- *Active responder*. Pulses of electromagnetic radiation are sent out by a source (interrogating pulses) and trigger a response from a *responder beacon*. The time interval between the sending and the receiving of a pulse is monitored and used to determine a distance.

- *Passive reflection*. Ranging is a technique that measures distance from the observer to a target, especially a far and moving target. Active methods use unilateral transmission and passive reflection.

Es. Radar, LIDAR (Light Detection and Ranging), Sonar, Ultrasonic range finding. Range 10m - 10km

- ***Interferometry methods***

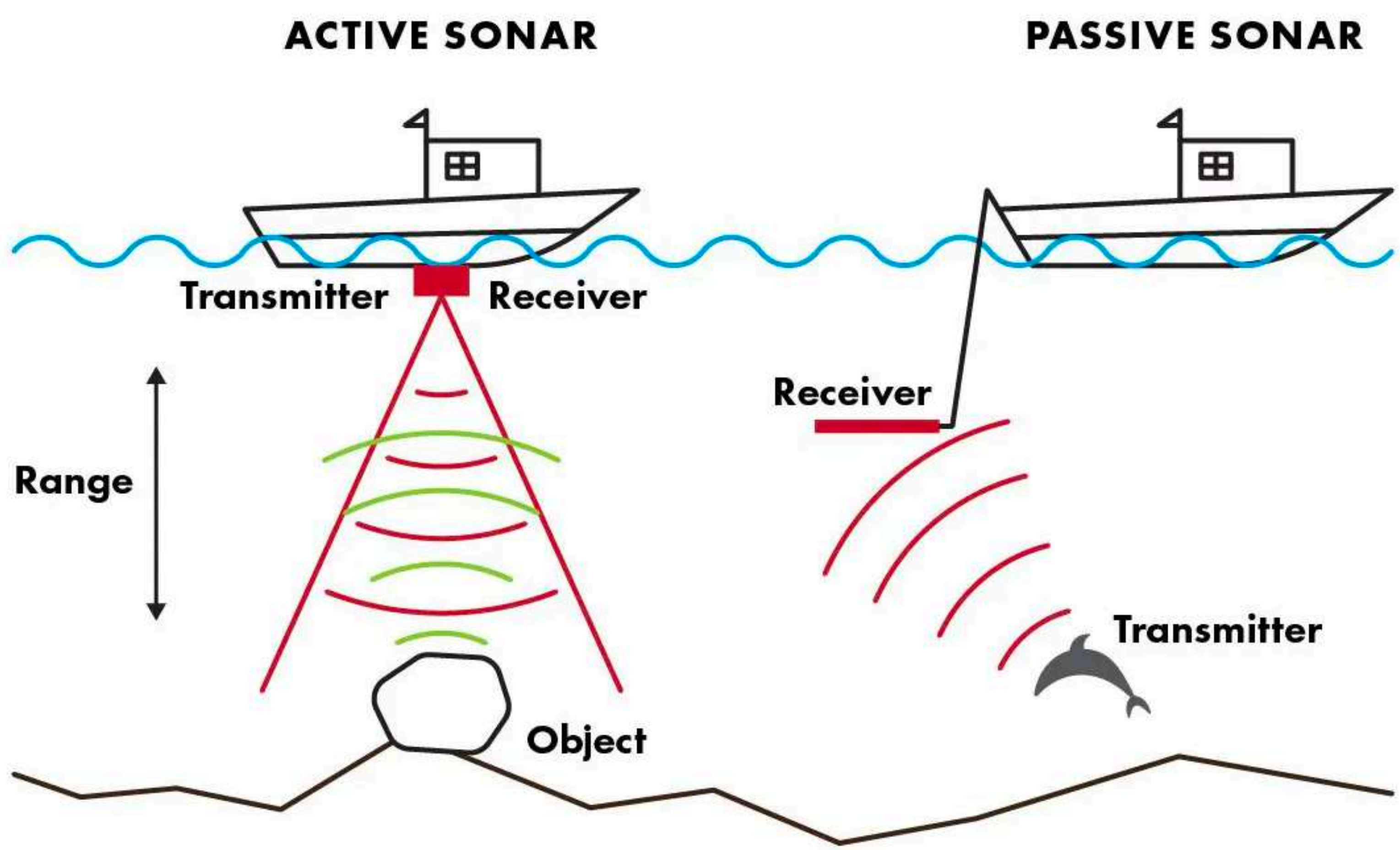
Utilise optical systems, analyse interference patterns of electromagnetic waves to achieve exceptional precision in distance measurements (es. $\Delta L/L \approx 10^{-9}$-$10^{-11}$)

DISTANCE MEASUREMENT

Distance from time measurement: active/passive receiver

Passive receiver: utilises sensors that listen for any waves coming from potential sources. When an object or creature emits sound/electro-magnetic waves, the sensor analyses it to determine the type of source.

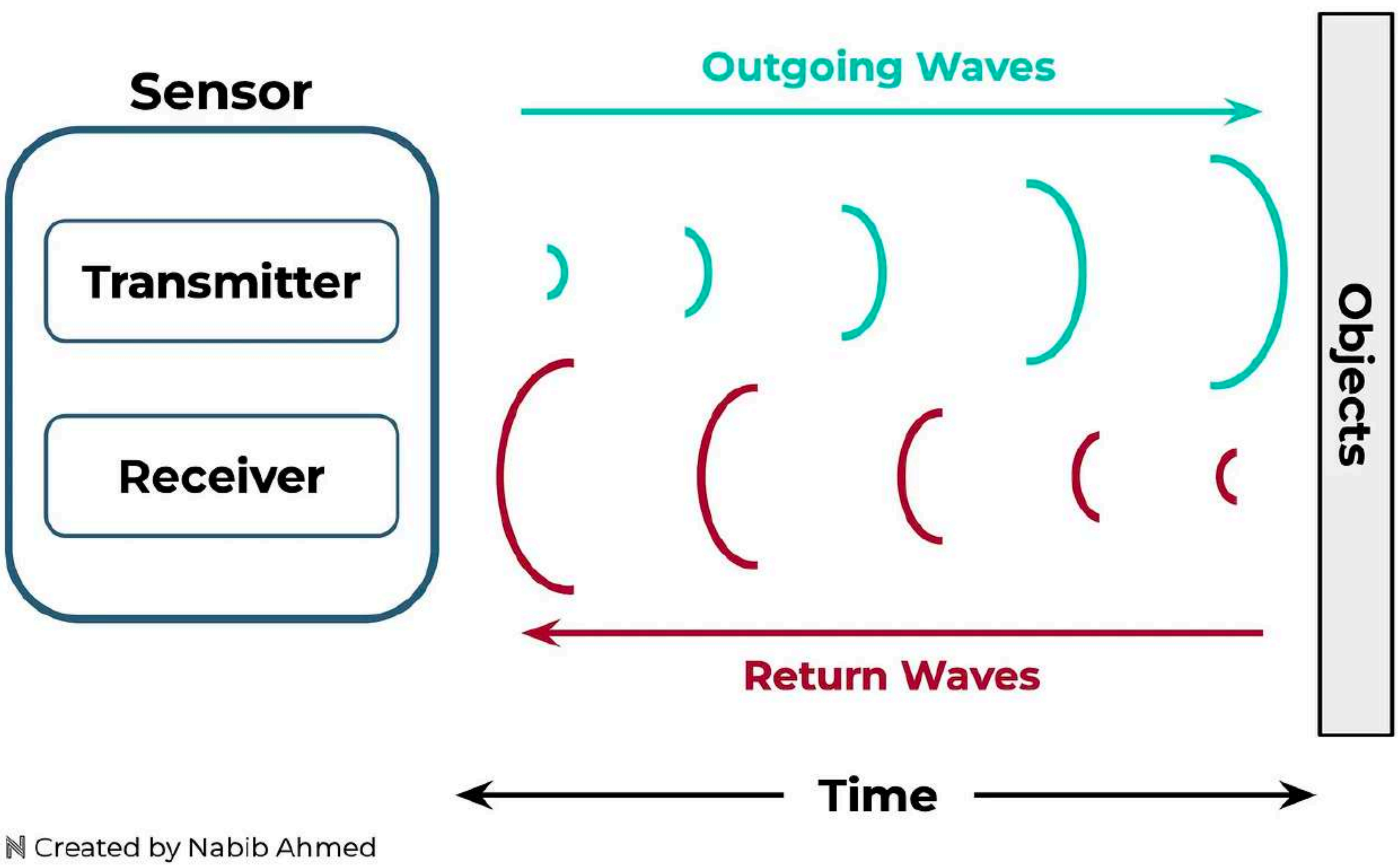
Active receiver: within the sensor, a transmitter emits sound/electro-magnetic waves, and a receiver waits for them to reflect from objects. By calculating the time it takes for the wave to return to the receiver, the distance to the object can be estimated.

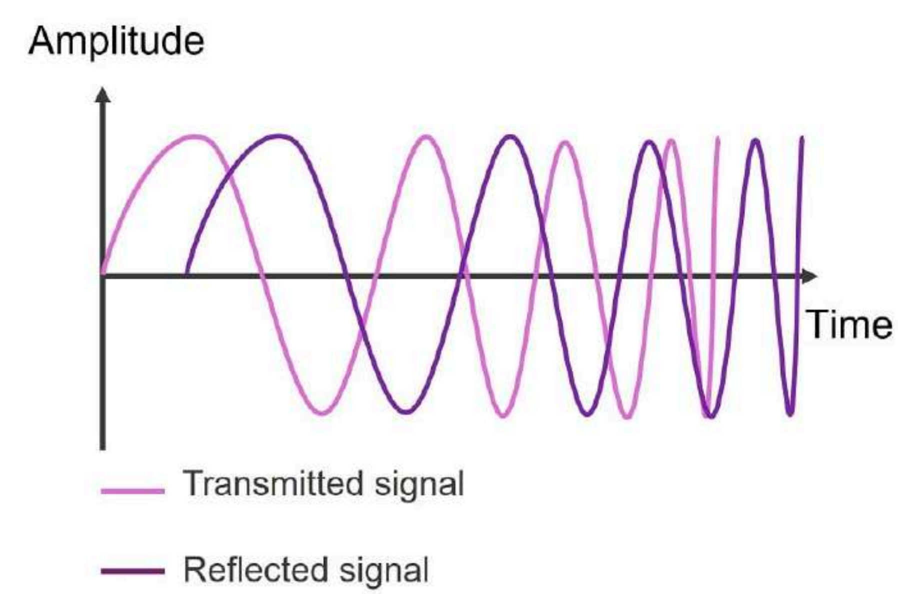


DISTANCE MEASUREMENT

Distance from time measurement: transmitter and receiver

A common technique for **sensors** to measure their environment is to shoot outgoing **electromagnetic/ mechanical waves** and wait for them to return. The outgoing waves will return if they hit something in the environment and are deflected back to the sensor. Based on the time it took for the return wave to come back as well as the speed of the wave, approximate distances between the sensor and the objects can be determined. Typically, in this setup, the sensor will have a **transmitter** that is sending outgoing waves and a **receiver** that is collecting return waves.





DISTANCE MEASUREMENT

Distance from time measurement: role of frequency for the sensors

- A sensor that uses higher frequency waves will provide better resolution of the environment. Intuitively, since the wave is oscillating more, it has a greater chance of hitting objects in the environment and detecting them, thus providing much better resolution.

- A higher frequency is being able to detect smaller objects, as there's more opportunity for the wave to collide into it. This can be very advantageous for situation were detailed information about environment is needed.

- A downside of higher frequency waves is that they lack range. Lower frequency waves have a longer wavelength, enabling them to travel farther and cover more distance.

- Another limitation of higher frequency waves is that they generally need more energy. This can be a constraint in situation where access to power or energy is limited (such as in sea or in space) or when energy capacity is low (such as with drones which have small batteries), making low frequency waves more preferable.

There's no one frequency that fits all situations. The frequency used will depend on the context / objective of the task and the trade-offs between low and high frequencies.

https://medium.com/@nahmed3536/the-wave-physics-behind-lidar-radar-infrared-ir-sonar-ultrasonic-sensors-721e99eacdf9

DISTANCE MEASUREMENT

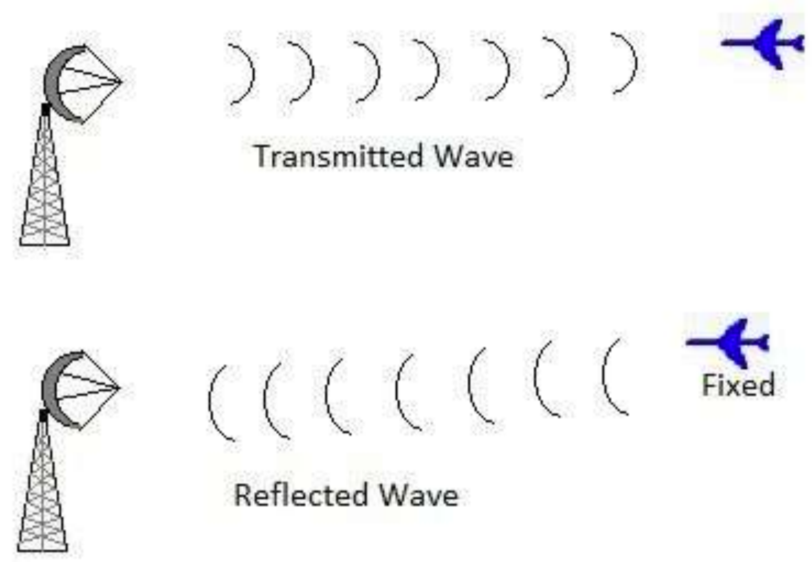
Distance from time measurement: transit-time & Doppler shift

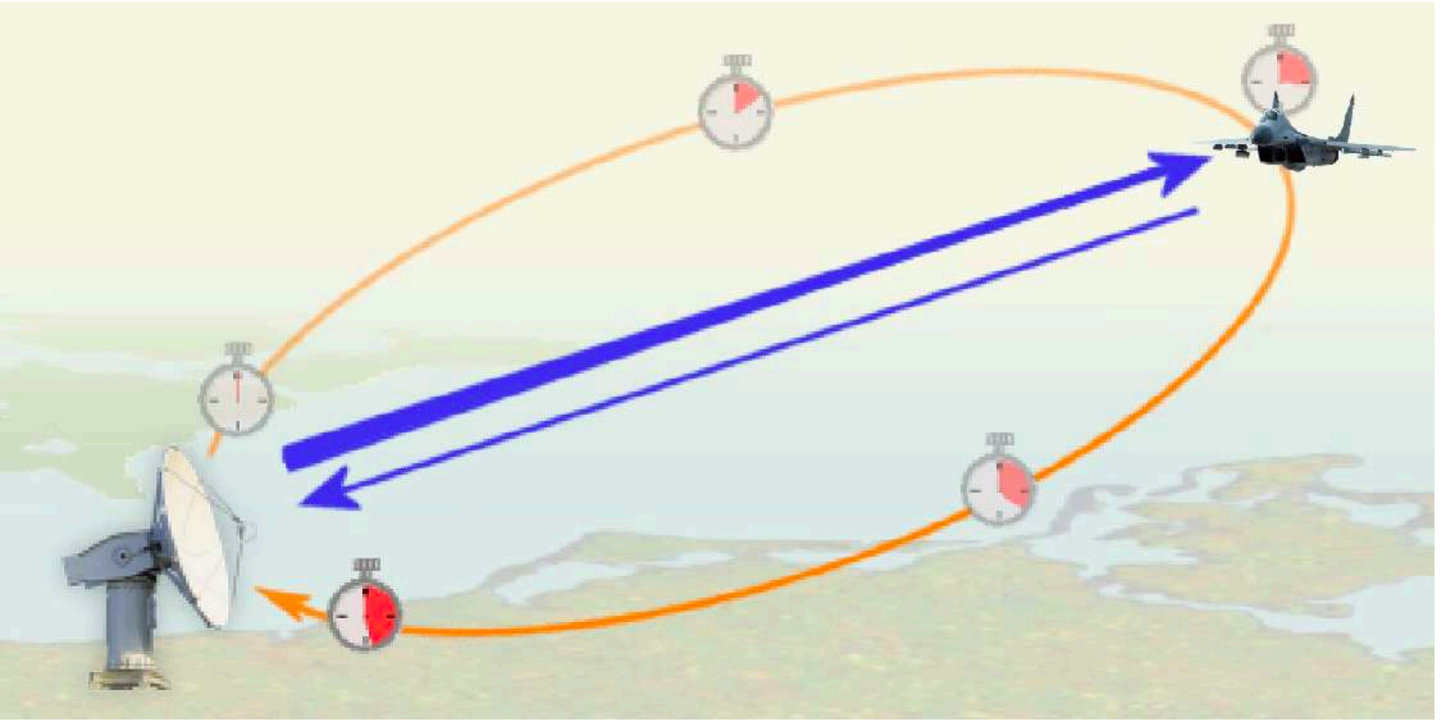
Distance measurement via transit-time and Doppler shift are two distinct methods used in different contexts, each with its strengths and limitations.

Transit-time measurement determines distance by calculating the time it takes for a signal, such as a pulse or wave, to travel to an object and return to the source. The time for the round trip is the transit time Δt, and the length ℓ is then $2\ell = \Delta t\ v$, with v the speed of propagation of the signal, assuming that is the same in both directions.

This method is often utilized in applications requiring precise **range measurements**, like radar systems, ultrasonic sensors, or time-of-flight (ToF) sensors in distance measurement tools.

It provides accurate distance calculations but might be affected by signal dispersion or reflections.





DISTANCE MEASUREMENT

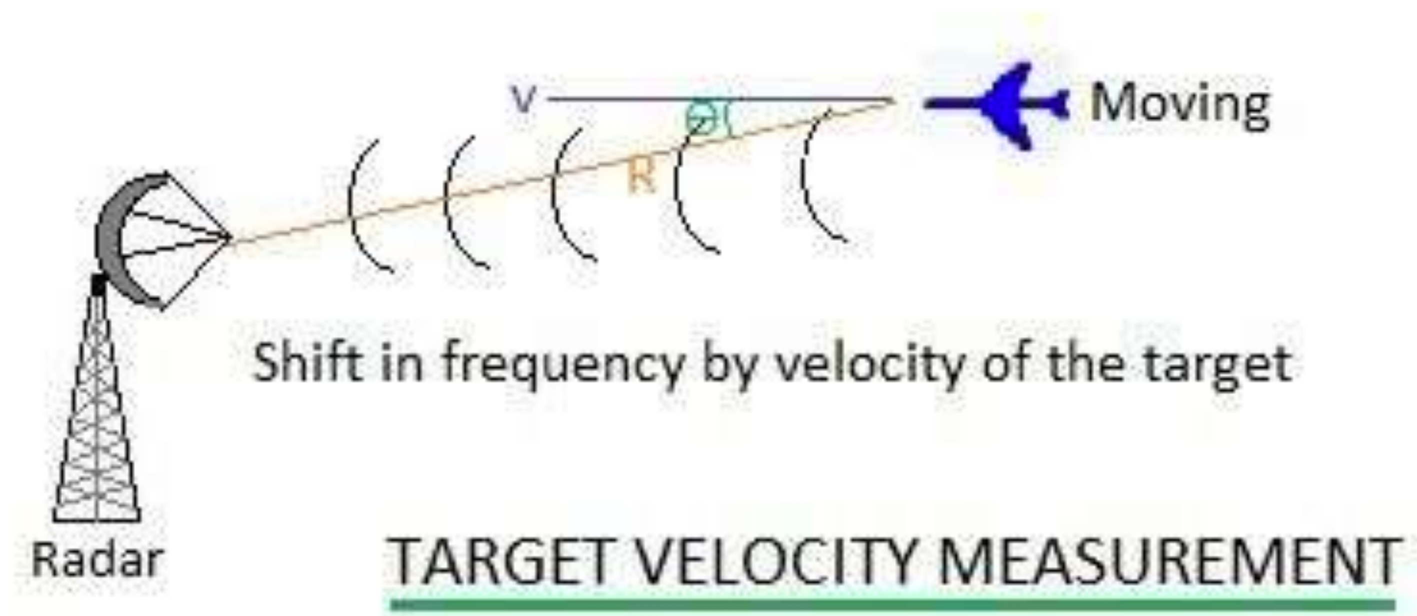
Distance from time measurement: transit-time & Doppler shift

Distance measurement via transit-time and Doppler shift are two distinct methods used in different contexts, each with its strengths and limitations.

Doppler shift measures distance based on changes in frequency caused by an object's motion relative to the observer or source of the signal.

It determines the **rate of change in distance over time** rather than the absolute distance itself.

Doppler shift is commonly employed in speed and velocity measurements, as in radar guns used by law enforcement to determine the speed of vehicles. While Doppler shift can swiftly estimate velocity, it requires additional calculations or assumptions to derive distance accurately.



DISTANCE MEASUREMENT

The Doppler effect

The Doppler effect describes the change in frequency or wavelength of a wave in relation to an observer's motion relative to the source of the wave. For instance, in the context of sound waves, when a source moves toward an observer, the perceived frequency increases, resulting in a higher pitch, while movement away from the observer leads to a decrease in frequency, resulting in a lower pitch. The formula for the observed frequency ($f_{observed}$) due to relative motion is given by:

$$f_{\text{observed}} = f_{\text{source}} \cdot \left(\frac{v + v_{\text{observer}}}{v - v_{\text{source}}} \right)$$

Where:

- f_{observed} = Observed frequency by the observer
- f_{source} = Frequency of the source
- v = Velocity of the wave in the medium
- v_{observer} = Velocity of the observer
- v_{source} = Velocity of the source

DISTANCE MEASUREMENT

Distance from time measurement: transit-time & Doppler shift

Transit-time and Doppler shift methods have their advantages:

- Transit-time excels in precise distance measurements but might encounter challenges in complex environments

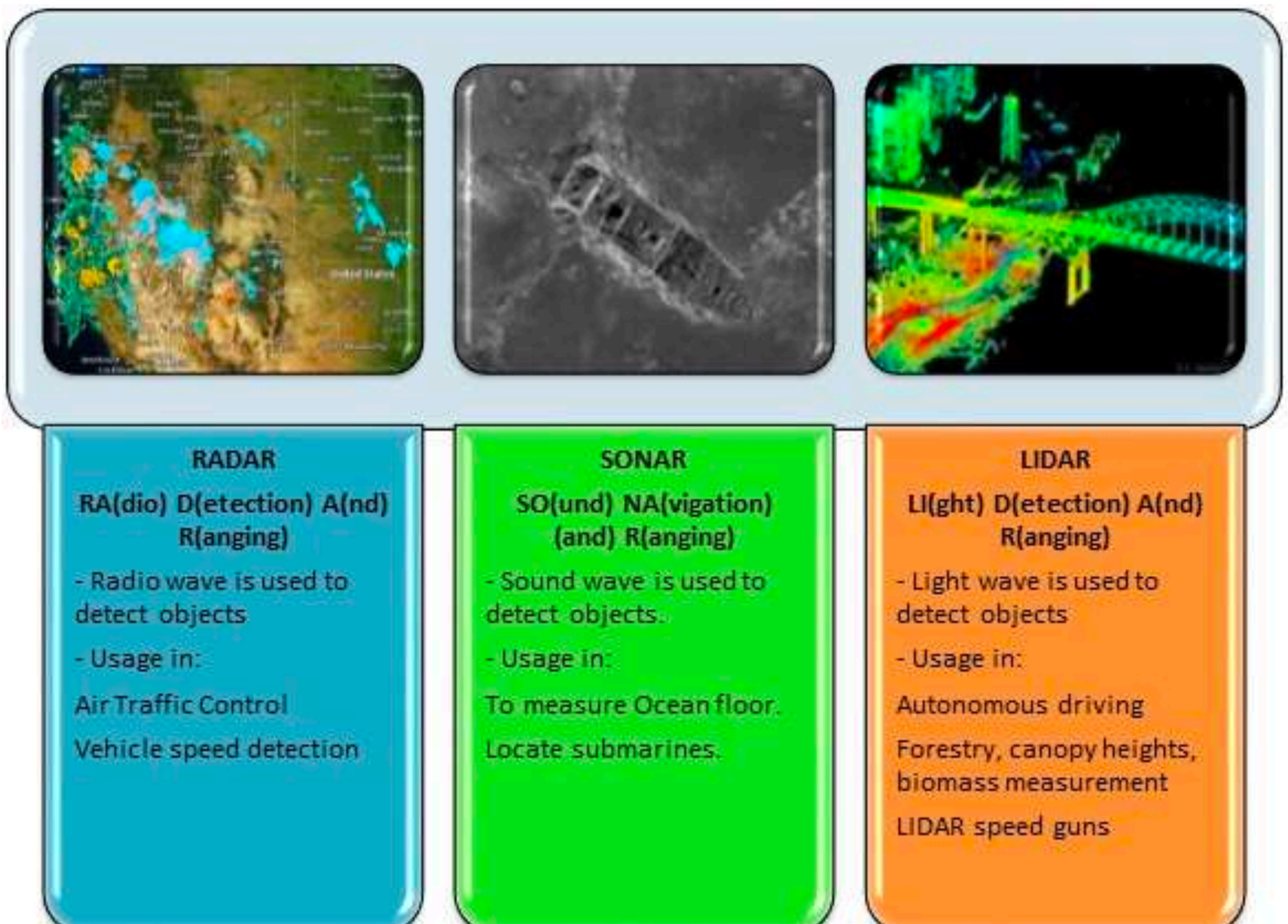
- Doppler shift is efficient for speed estimation but may necessitate further computations to infer distance accurately.

The selection of a method often depends on the specific requirements of the application, the nature of the object being measured, and environmental factors impacting signal propagation.

DISTANCE MEASUREMENT ON EARTH

Range measurement and sensors wavelengths

Radar, sonar, lidar, infrared and ultrasound are distinct technologies used for range measurements in various domains, each employing different wavelengths and principles tailored to specific applications and environments.



DISTANCE MEASUREMENT ON EARTH

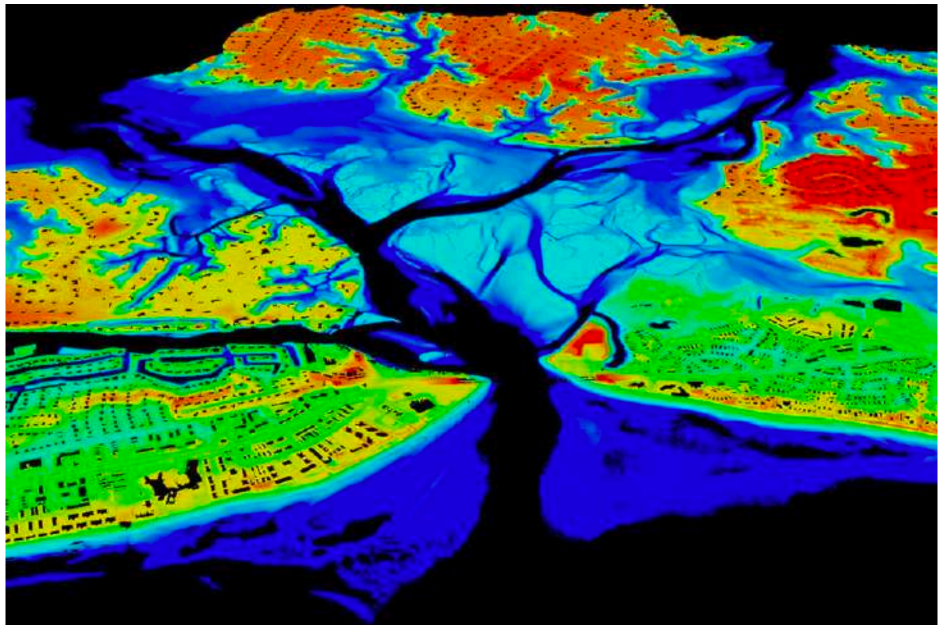
Range measurement

1. **Lidar** (Light Detection and Ranging):

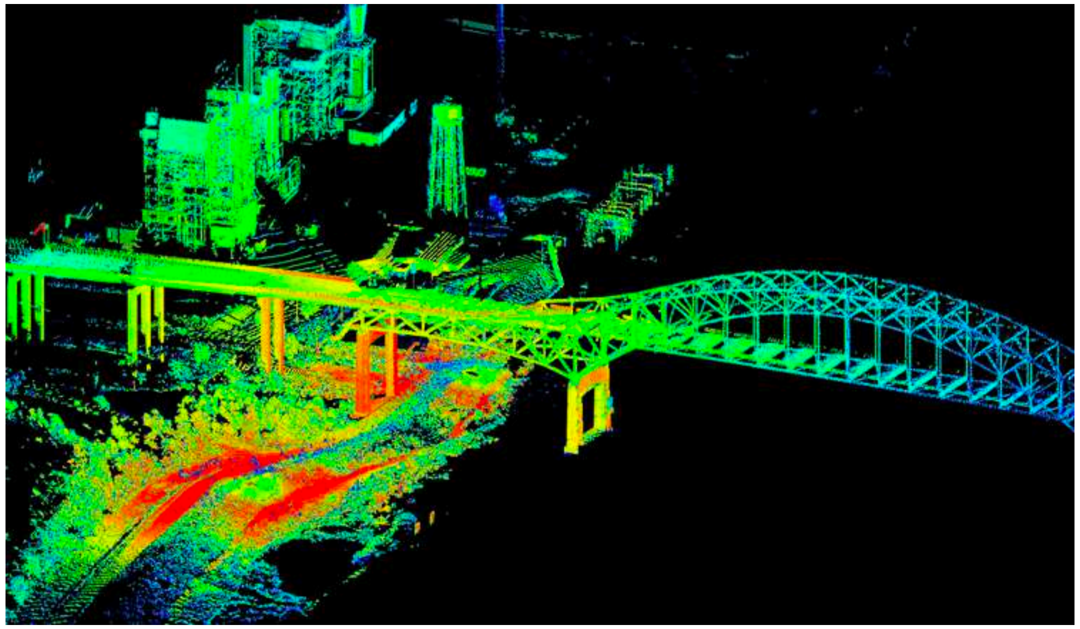
- Frequency: Utilizes laser pulses in the optical spectrum, usually in the infrared or visible range (ranging from hundreds of THz to several hundred GHz).

- Effective Distances: Lidar systems are effective for *moderate ranges*, from a few m to a few km, offering high precision in 3D mapping and object detection.

- Applications: Valuable for *high resolution mapping -* geospatial mapping, urban planning, autonomous vehicles, forestry, and environmental monitoring due to its high accuracy.



https://oceanservice.noaa.gov/facts/lidar.html



https://www.gislounge.com/lidar/

DISTANCE MEASUREMENT ON EARTH

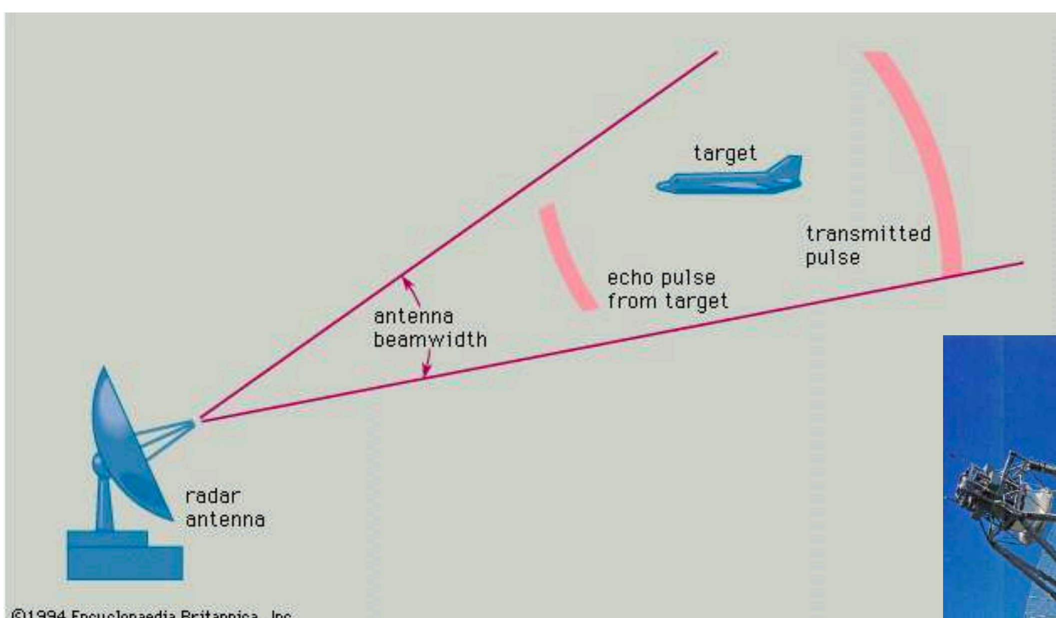
Range measurement

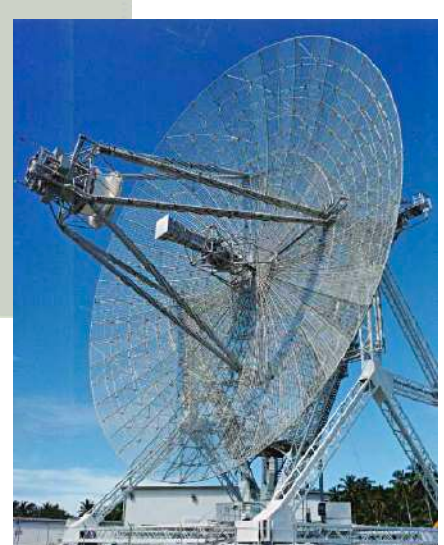
2. **Radar** (Radio Detection and Ranging):

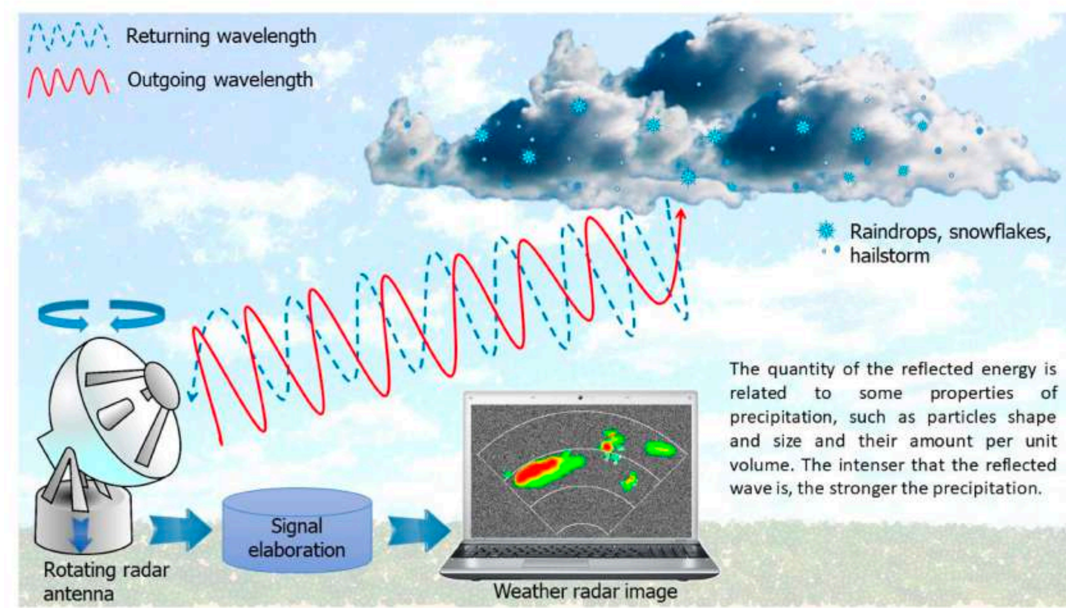
- Frequency: Operates within the radio wave spectrum (typically from MHz to GHz).

- Effective Distances: Radar systems can cover *short to long distances*, from a few m to hundreds of km.

- Applications: Widely employed in air traffic control for aircraft detection, weather forecasting for precipitation tracking, and military surveillance due to its ability to cover long distances and operate in various weather conditions.







DISTANCE MEASUREMENT ON EARTH

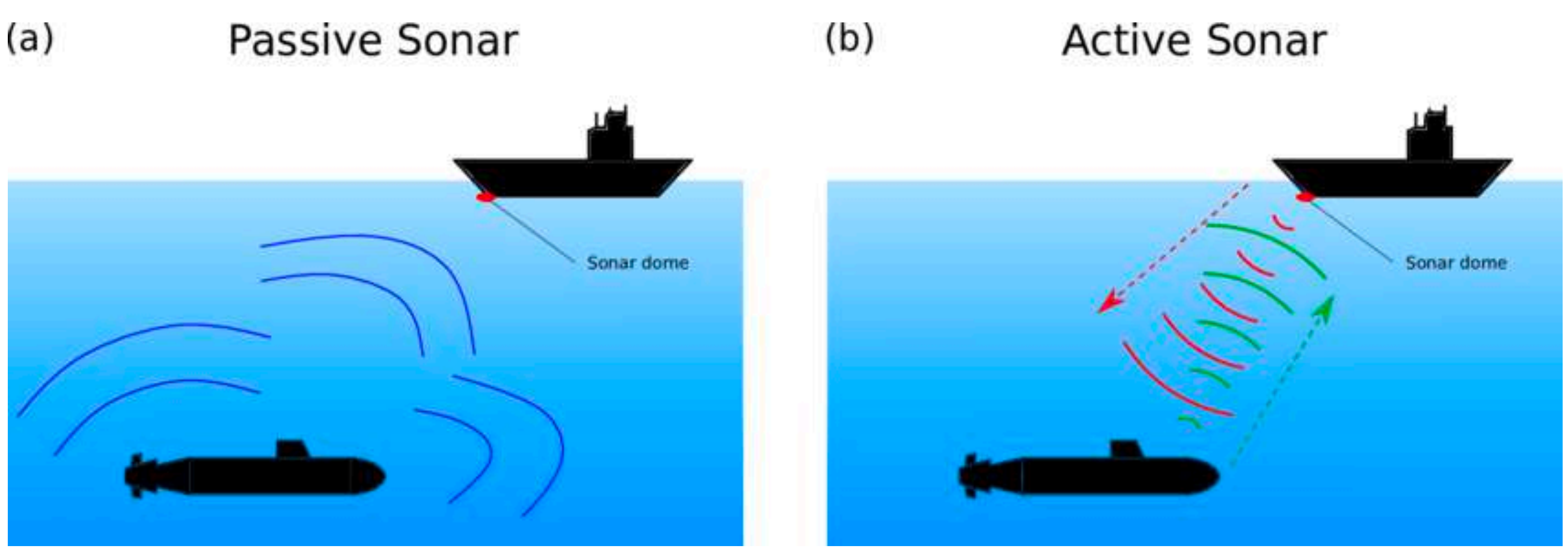
Range measurement

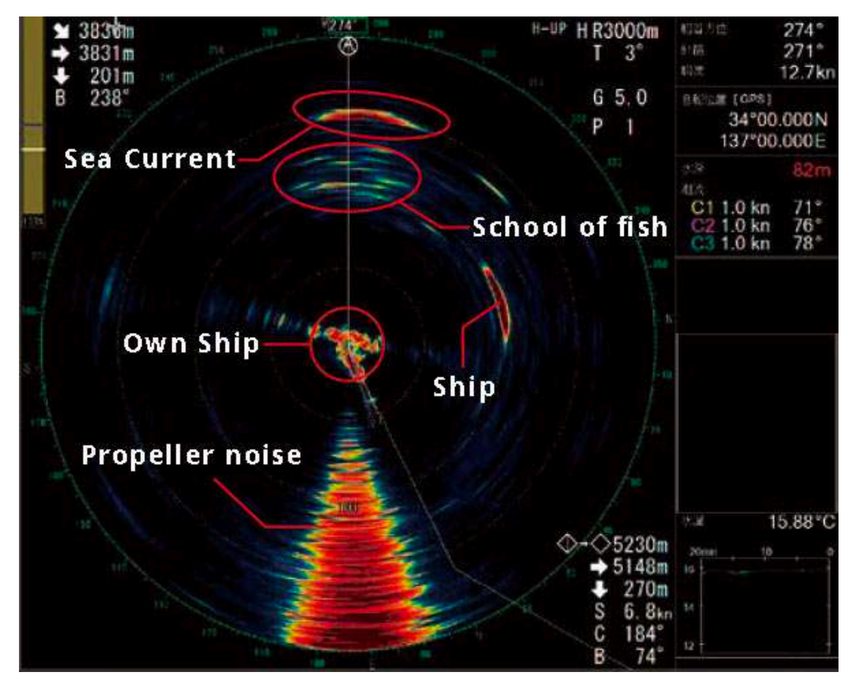
3. **Sonar** (Sound Navigation and Ranging):

- Frequency: Utilises sound waves, typically ultrasonic frequencies (20 kHz to several MHz) with high *power*, especially in underwater applications.

- Effective Distances: Suitable for shorter ranges in the context of *underwater navigation* and mapping, ranging from a few m to several km depending on water conditions.

- Applications: Commonly used in marine navigation, fisheries, underwater surveying, and object detection beneath the water's surface.





DISTANCE MEASUREMENT ON EARTH

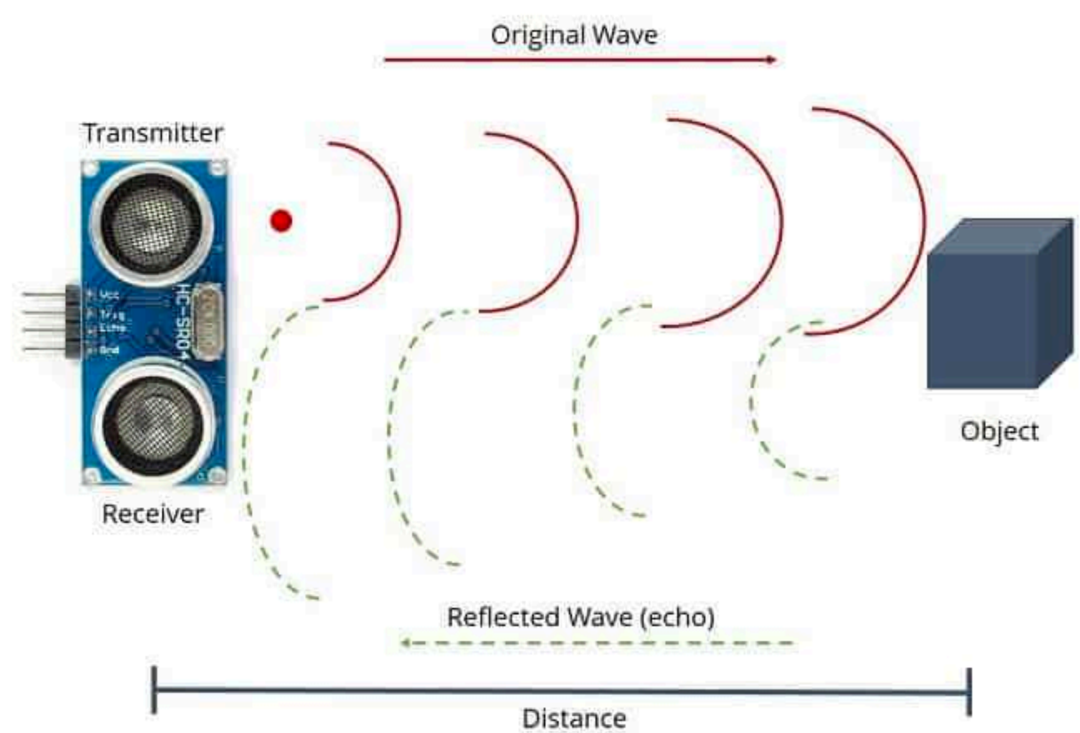
Range measurement

4. **Ultrasound**:

- Frequency: Operates at high-frequency sound waves (typically from 20 kHz to several MHz).

- Effective Distances: Suitable for relatively *short distances*, from a few mm to a few m, depending on the application.

- Applications: Widely utilised in medical imaging for *safe diagnostics*, industrial applications like flaw detection in materials, and distance measurement in sensors where safety and non-invasiveness are crucial.



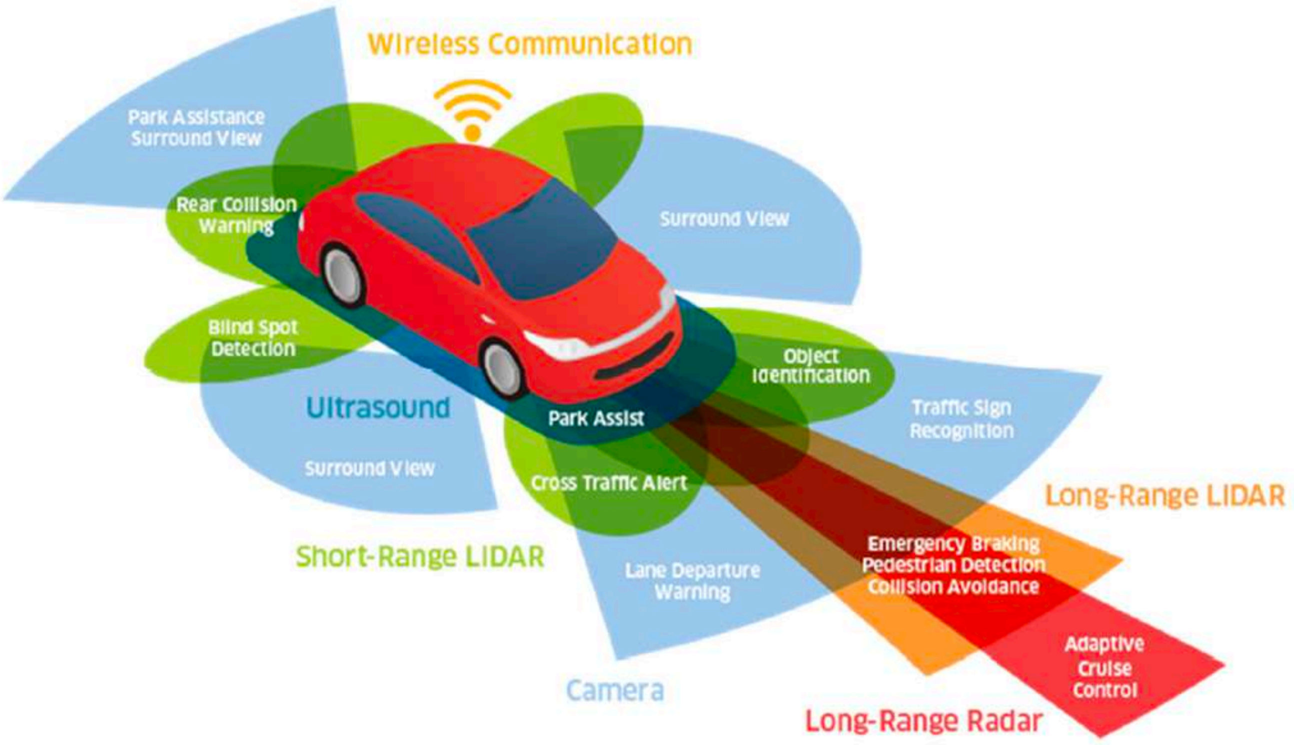
DISTANCE MEASUREMENT ON EARTH

Range measurement. Example: *Self-driving cars*

Autonomous Vehicles (AV) are vehicles that can operate with minimal to no human supervision. They are able to localize themselves, navigate in spaces, and where applicable, complete tasks. The field of AV is interdisciplinary, involving tools from computer science, artificial intelligence, mechanical and electrical engineering, mathematics, and more.

Higher frequency allows to detect smaller objects, which is advantageous for situations were detailed information about environment is needed. Lower frequency waves however can provide information further away from the car and enable more time for the autonomous vehicle to process and react.

Many current AV solutions leverage both RADAR (lower frequency wave) and LiDAR (higher frequency wave) sensors in tandem, for higher resolution for near objects with LiDAR and awareness of far objects with RADAR



https://www.nature.com/articles/s41598-023-40961-5

DISTANCE AND POSITION MEASUREMENT ON EARTH

Measuring position: trilateration vs triangulation

Trilateration and triangulation are geometric techniques used to determine positions in space, but they differ in their principles and the way they calculate locations.

1. Trilateration:

- Principle: Trilateration calculates positions by measuring distances between known points (usually fixed reference points or nodes) and an unknown point.

- Process: In trilateration, the distances to the unknown point from at least three fixed reference points (which can be satellites in GPS or stationary beacons) are measured. Using these distances, the unknown point's position is determined by finding the intersection of spheres (in 3D) or circles (in 2D) centered around the fixed points.

- Use: Widely employed in GPS systems, surveying, and positioning technologies where distances between fixed reference points and an unknown location can be accurately measured.

DISTANCE AND POSITION MEASUREMENT ON EARTH

Measuring position: trilateration vs triangulation

2. Triangulation:

- Principle: Triangulation calculates positions by measuring angles between known points and an unknown point.

- Process: In triangulation, angles between at least two known reference points and the unknown point are measured. By forming triangles and using trigonometric principles, the unknown point's position is determined.

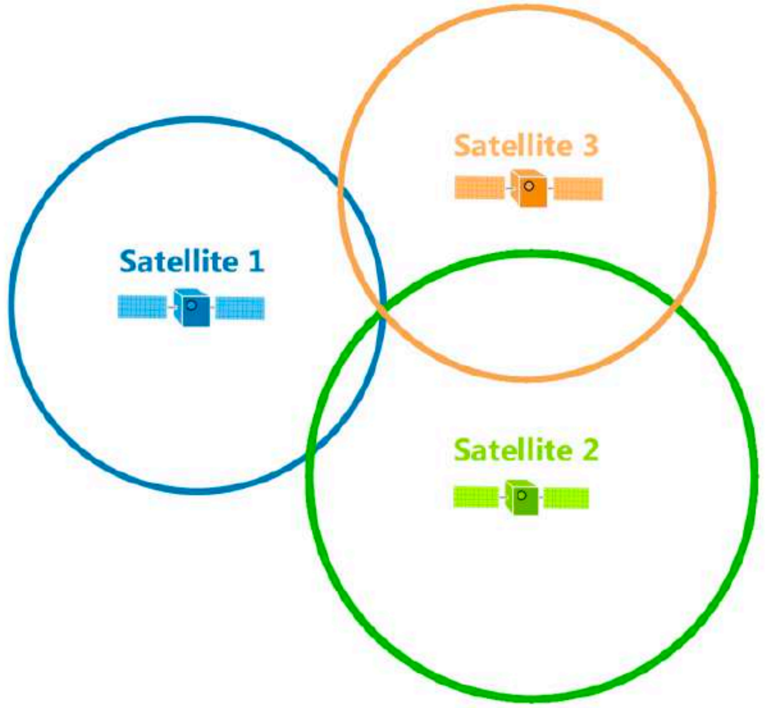
- Use: Historically used in surveying and land measurement, where angle measurements between distant landmarks or surveying instruments were employed to determine positions.

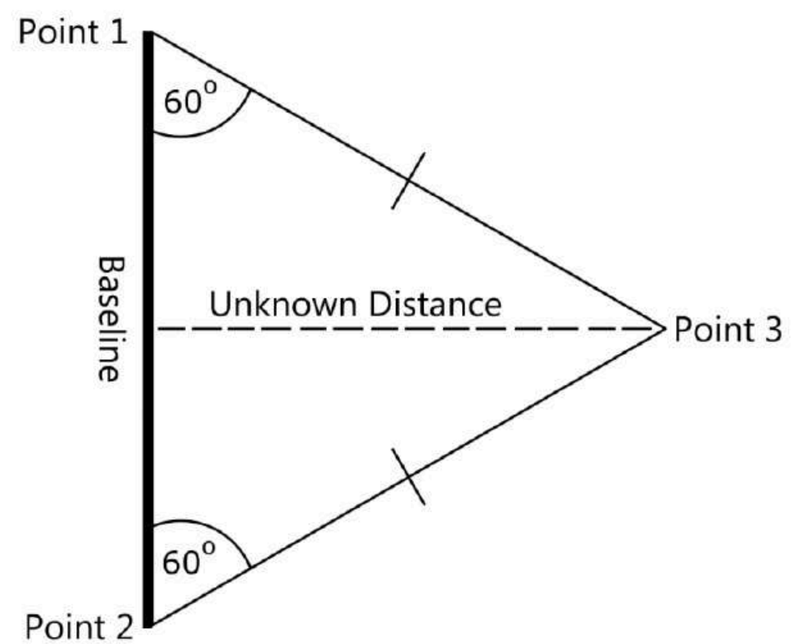
DISTANCE AND POSITION MEASUREMENT ON EARTH

Measuring position: trilateration vs triangulation

In essence, trilateration focuses on measuring distances to locate an unknown point by intersecting spheres or circles, while triangulation relies on measuring angles to determine positions by forming triangles.

Both methods are fundamental in various fields, from geolocation and navigation to surveying and engineering, each offering distinct advantages in specific applications based on the available measurement tools and requirements.





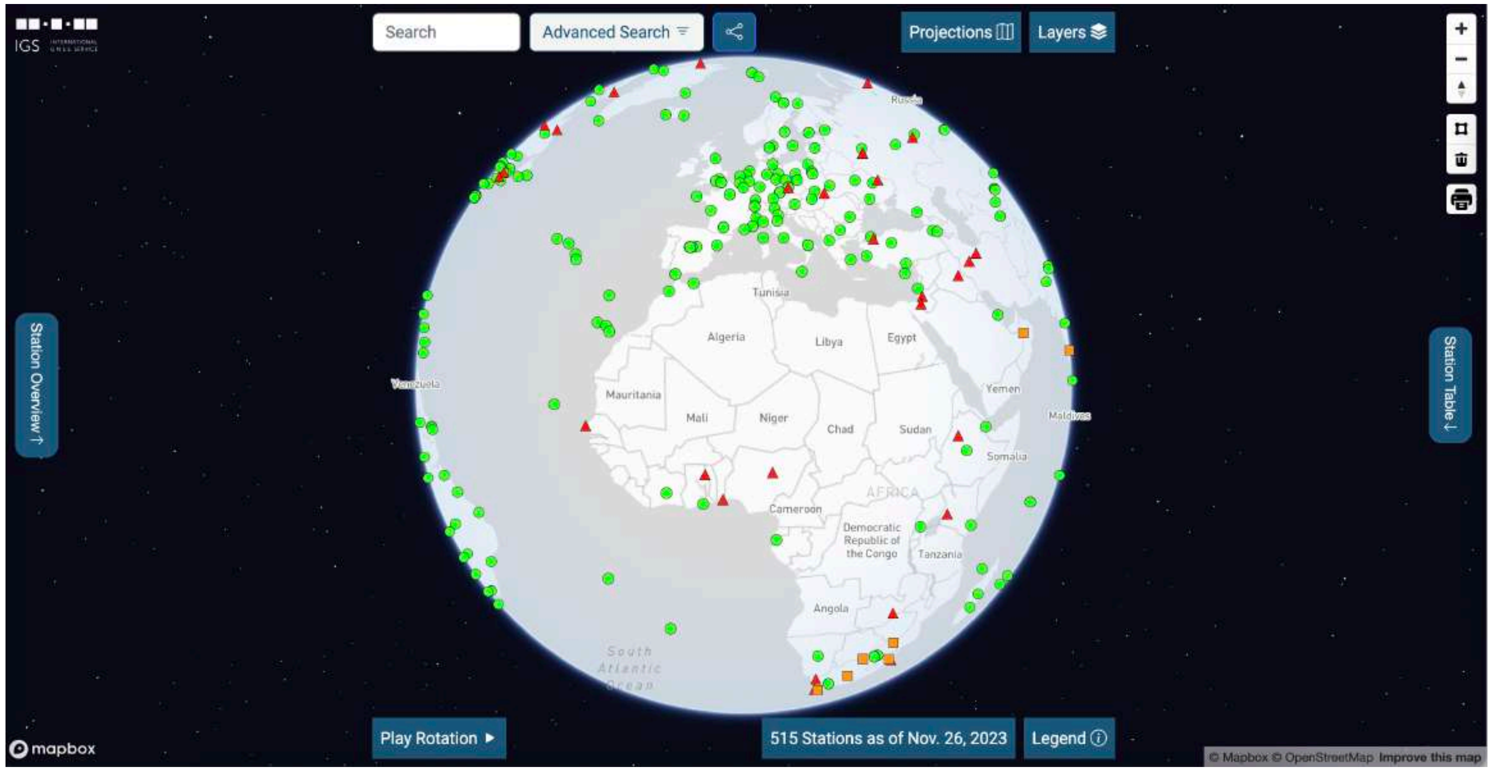
POSITION MEASUREMENT ON EARTH FROM SPACE

The Global Navigation Satellite System (GNSS)

A satellite navigation or satnav system is a system that uses satellites to provide autonomous geopositioning. A satellite navigation system with global coverage is termed global navigation satellite system (GNSS).

As of 2023, four global systems are operational: the United States’s Global Positioning System (GPS), Russia's Global Navigation Satellite System (GLONASS), China's BeiDou Navigation Satellite System, and the European Union's Galileo.

Satellite navigation allows satellite navigation devices to determine their location (longitude, latitude, and altitude/elevation) to high precision (within a few centimeters to meters) using time signals transmitted along a line of sight by radio from satellites.



https://igs.org/

POSITION MEASUREMENT ON EARTH FROM SPACE

The Global Positioning System (GPS)

The GPS operates through a network of satellites orbiting the Earth. These satellites continuously transmit precise timing signals and location data to GPS receivers on the ground. The system functions based on the principle of trilateration, which involves determining positions by measuring distances from known locations.

GPS receivers passively receive signals from multiple satellites, typically at least four, and use the time it takes for these signals to reach the receiver to calculate the distances to each satellite. By measuring the time delay between when the signal was sent by the satellite and when it was received, the receiver can determine the distance by multiplying the signal's travel time by the speed of light.

Once the distances to at least four satellites are known, the GPS receiver can pinpoint its location by intersecting the spheres or three-dimensional spheres centered at the known satellite positions, where the receiver lies on the intersection of these spheres. The receiver's position is then calculated by using trilateration to find the intersection point, providing accurate latitude, longitude, altitude, and timing information.

GPS receivers continuously track multiple satellite signals to improve accuracy, compensating for signal delays caused by atmospheric conditions, satellite orbits, and the receiver's motion. The combination of signals from different satellites allows for more precise location determination, enabling a wide array of applications, from navigation for personal devices to precision timing, surveying, mapping, and various scientific and military uses.

SPEED AND DIRECTION

The concept of speed

Speed quantifies the rate of motion of an object or particle and is calculated as the distance traveled per unit of time.

- Average speed v_{avg} is given by $v_{avg} = \frac{d}{T}$

where d represents the distance traveled, and T signifies the time taken to cover that distance.

- Instantaneous speed v(t) at a specific moment is derived from the derivative of distance with respect to time $v(t) = lim_{\Delta t \to 0} \frac{\Delta d}{\Delta t}$

where Δd is an infinitesimally small change in distance and Δt is an infinitesimally small change in time.

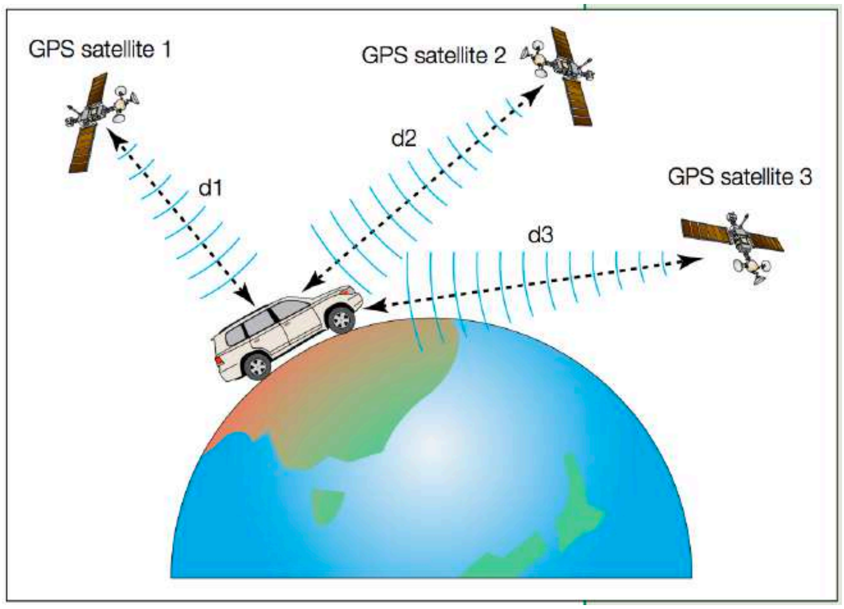
The measurement of speed is fundamental in physics, engineering, and various practical applications, aiding in analyzing motion, determining velocity, designing transportation systems, and ensuring compliance with speed limits for safety on roads and in various moving systems.

SPEED MEASUREMENT

Speed measurement encompasses various techniques tailored to different contexts and precision requirements, employing diverse methodologies and instruments. Some common methods include:

1. *Radar/Laser Guns*: Utilize the Doppler effect by emitting radio waves or laser beams and measuring the change in frequency reflected off a moving object to determine its speed. Widely used in law enforcement for traffic speed monitoring.

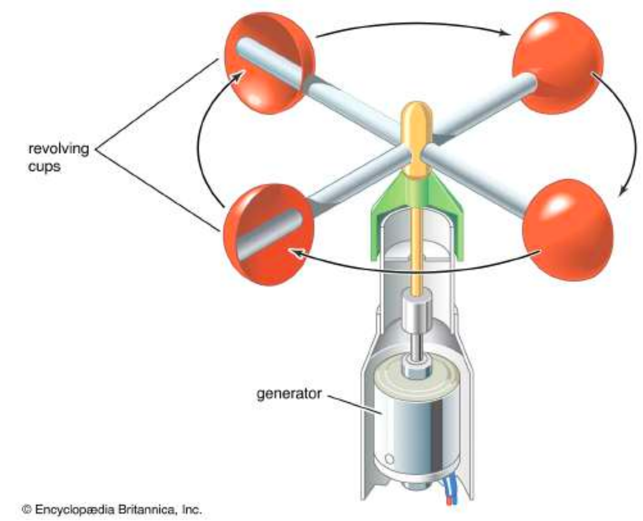
2. *GPS Systems*: Determine speed by tracking the movement of an object using satellite signals. GPS receivers calculate speed based on changes in position over time, offering accurate velocity measurements.



3. *Accelerometers*: often integrated into devices or systems, gauge changes in velocity or acceleration directly, enabling speed calculations based on alterations in motion

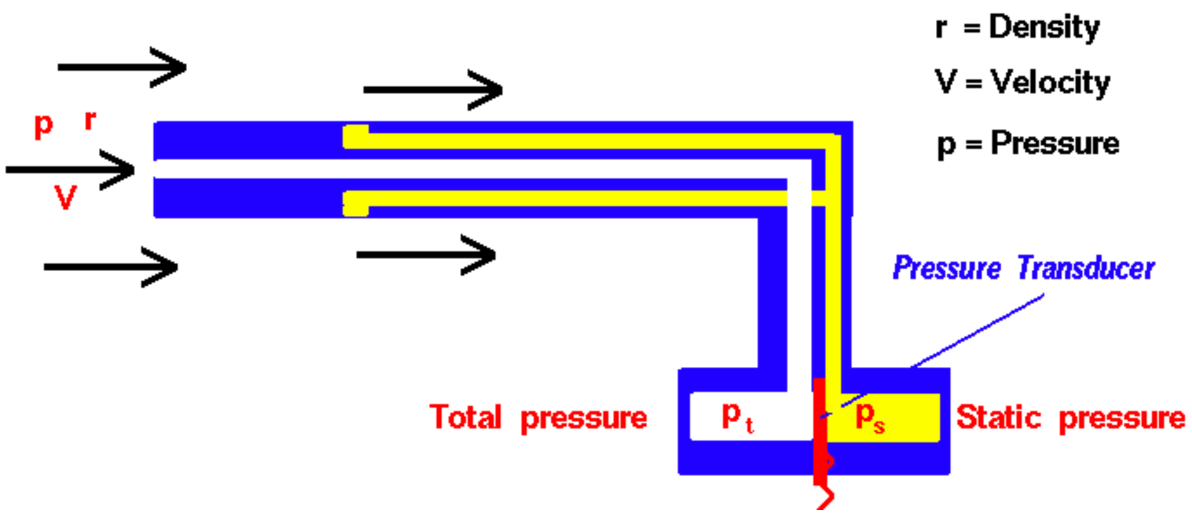
SPEED MEASUREMENT

4. *Anemometers*: Measure wind speed but can be adapted to measure the speed of a moving object by utilizing the airflow caused by its motion, commonly used in meteorology and airflow analyses.



5. *Tachometers*: Specifically designed for measuring the rotational speed of machinery or engines, using sensors to track revolutions per minute (RPM) or cycles per second.

5. *Pitot Tubes*: Gauge airspeed in aviation by measuring the difference between total pressure and static pressure to calculate the speed of an aircraft relative to the air.



These techniques employ various principles, such as the Doppler effect, GPS tracking, airflow measurement, or rotational motion sensing, catering to specific applications across transportation, meteorology, aviation, engineering, and scientific research. Selection of a method depends on factors like accuracy needs, environmental conditions, and the nature of the moving object or system being measured.

SPEED AND ACCELERATION MEASUREMENT

Accelerometers

Speed measurement using accelerometers involves assessing changes in velocity or acceleration to derive an object's speed.

Accelerometers, sensitive to inertial forces, detect accelerations along multiple axes, allowing determination of changes in motion. By integrating these accelerations over time, velocity can be derived, and further integration provides displacement or position.

However, direct measurement of speed solely from accelerometers can accumulate errors due to drift or integration inaccuracies over time. To mitigate this, additional calibration, fusion with other sensors like gyroscopes or GPS, and advanced algorithms are employed for more accurate speed estimation.

Widely integrated into various devices, vehicles, and systems, accelerometers play a key role in measuring speed, enabling precise motion tracking, navigation, and performance monitoring in applications ranging from automotive systems to wearable devices and industrial machinery.

SPEED AND ACCELERATION MEASUREMENT

Accelerometers

Principle of operation: A lumped spring–mass–damper (k–m–b) model schematically represents an accelerometer. The acceleration of the frame (a), which is to be sensed, manifests as the inertial force (ma) on the mass.

The movement of the frame is denoted by x and that of the mass by y. The net extension of the spring and the damper will thus be z=y–x.

The equation of motion, by summing the forces—inertial, damping, and spring forces—to zero, is then given by:

$$m\ddot{y}+b(\dot{y}-\dot{x})+k(y-x)=0$$

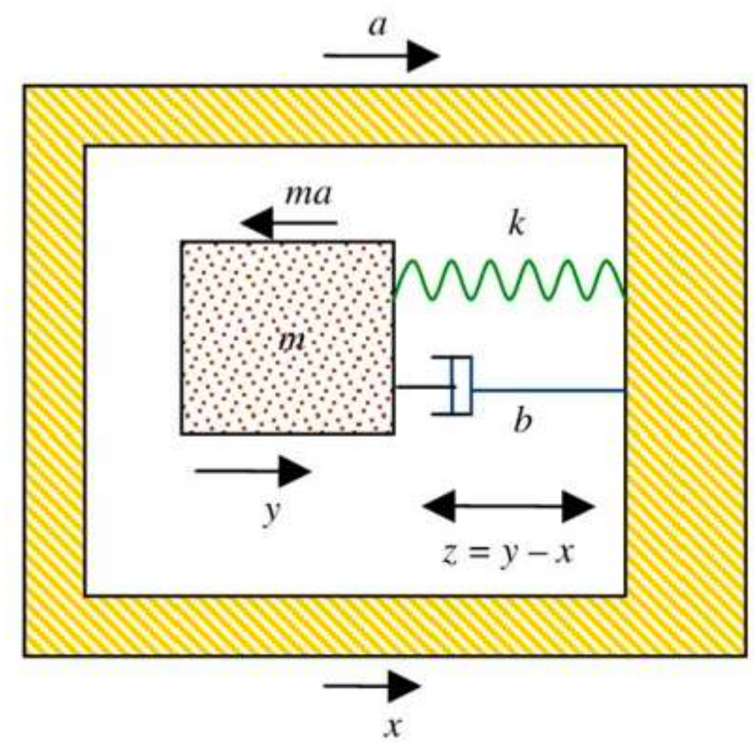
By substituting z = y–x and assuming that frame's excitation is harmonic, x= X sin(ωt) with amplitude X, and frequency ω.

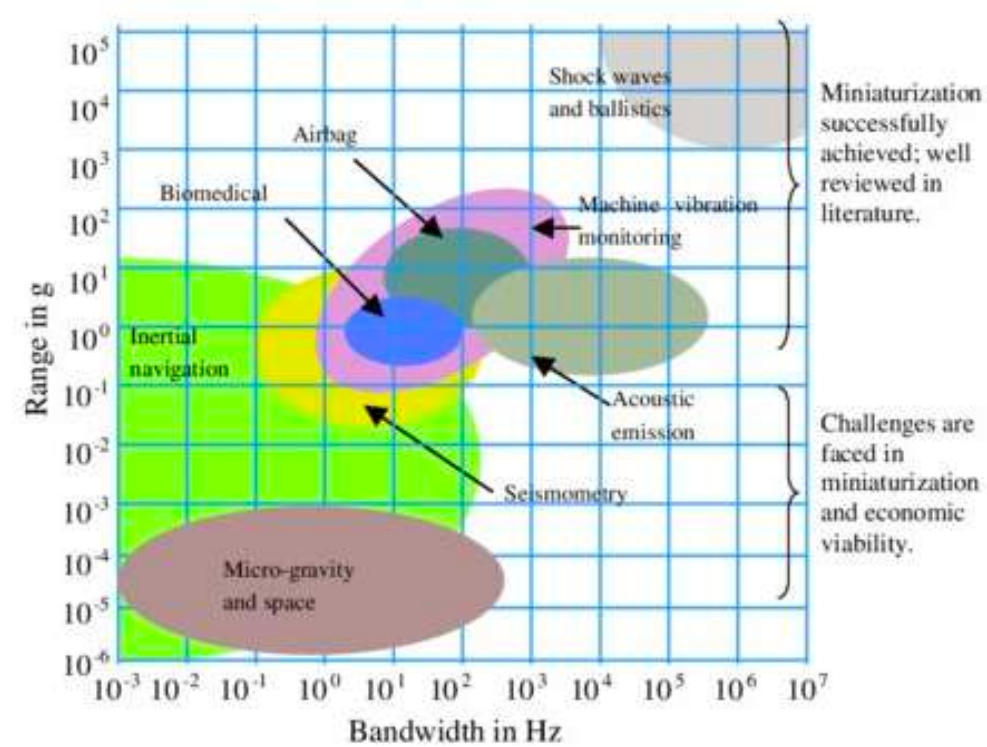
$$m(\ddot{z}+\ddot{x})+b\dot{z}+kz=0$$

$$\Rightarrow m\ddot{z}+b\dot{z}+kz=-m\ddot{x}=m\omega^2 X\sin\omega t$$

By denoting the amplitude of z as Z, and when operated at frequencies much less than the resonance frequency, i.e., when $\omega \ll \omega_n$

$$Z=\frac{a}{\omega_n^2}$$





https://www.researchgate.net/publication/239542403_MicromachinedHigh-Resolution_Accelerometers

SPEED AND ACCELERATION MEASUREMENT

Accelerometers

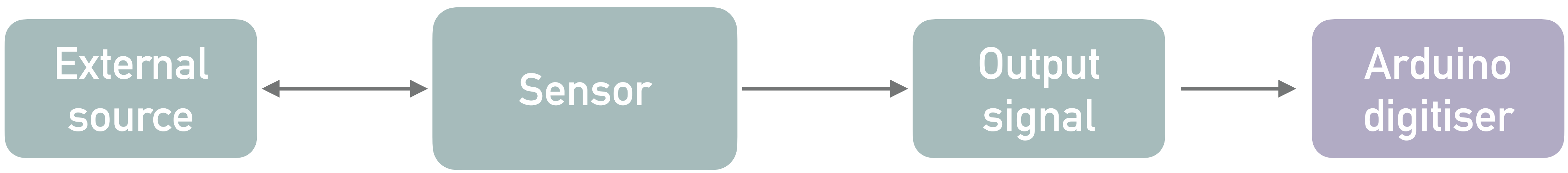
Types of Accelerometer

- **Capacitive MEMS Accelerometer.** The MEMS stands for Micro-Electro-Mechanical-System. MEMS is a fabrication technology. In this type of accelerometer, the changes in capacitance are detected instead of a change in resistance. Most mobile devices use this MEMS accelerometer.

- **Piezoresistive Accelerometer.** It measures the vibrations by changes in resistance. This is the accelerometer that works as DC responsive and proves efficient while measuring very little vibrations, for example, gravity vector.

- **Piezoelectric Accelerometer.** In this type the sensors are made of crystals or ceramics like lead zirconate, lead titanate, etc. This sensor absorbs the vibrations and produces the same amount of electrical signals.

EXAMPLE: ULTRASOUND DETECTOR/ACCELEROMETER READOUT CHAIN



- Source: element in space (static / in motion)
- Sensor: ultrasounds detector / accelerometer
- Read the signal output: Arduino digitiser

See Lab.3

BACKUP

SENSING THE ENVIROMENT

- Sources
  - Temperature & pressure: sensors & platforms
  - Distance and position: us, laser, gps —> lab: exp us
  - Speed: wind speed, antropic speed —> lab: exp accelerometers (ex automatic drive)
  - Vibrations: seismos —>
  - Acoustic —> lab: exp mics
  - Radiations: particle () & light (energy) —> lab: show cont geiger, and photodiodes or solar cell