اصول علم ربات – اسلاید دهم

Fundamentals of Robotics – Slide 10

Sensors I

دکتر مهدی جوانمردی

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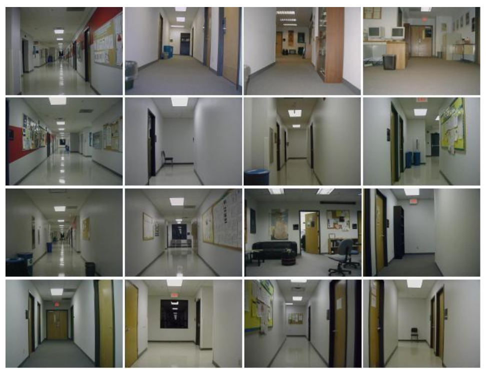
[slides adapted from Gianni Di Caro, @CMU with permission]

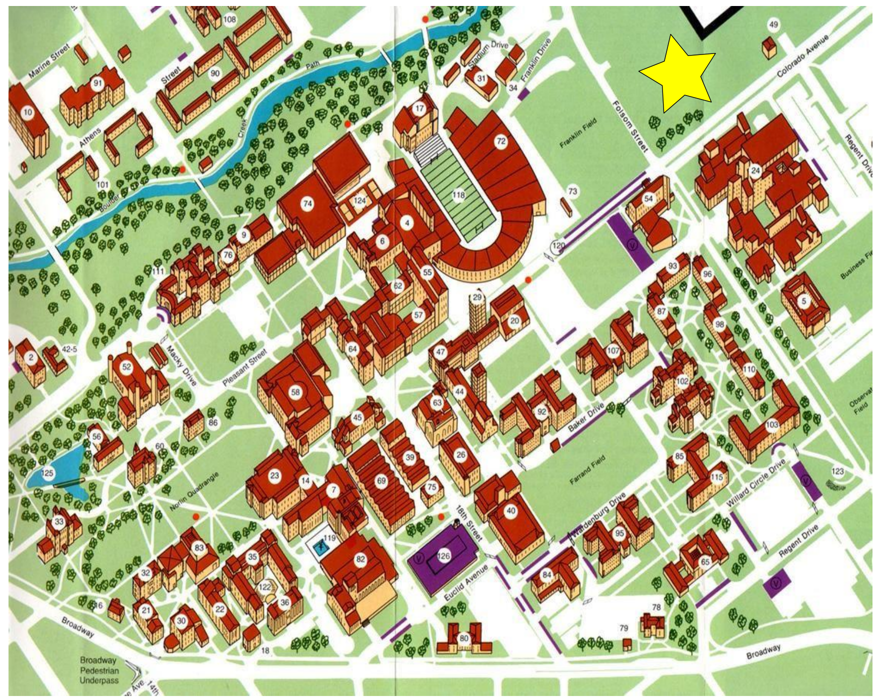
Navigation tasks for mobile robots



Where am I?

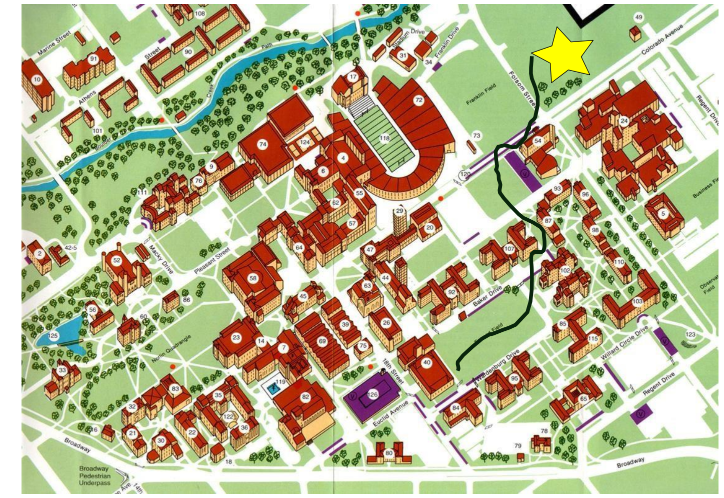
Localization
(State estimation)

Reference system
Map



Where am I going?

Representation
+
Mapping



How do I get there?

Planning (Deliberative)
Motion Control (Feedback)
Behaviors (Reactive)

Obstacle avoidance

Sensors

Sensor types

The robot can measure its **local / global position** and/or **movement**, as well as the **presence of objects** or **useful landmarks** through the use of *internal* and/or *external* sensing actions:

Sensing direction

Sensing modality

- ***Proprioceptive sensors:*** measure values **internally to the system** (robot). Examples are: motor speed, angular velocity of robot, battery status
- ***Exteroceptive sensors:*** gather information **from the robot environment**, such as distance to objects, intensity of the ambient light, radio signals

- ***Passive sensors:*** Measure energy coming from the environment
- ***Active sensors:*** Emit their proper energy and measure the reaction, potentially more effective but depends on the characteristics of the environment

Sensor taxonomy

General classification (typical use)	Sensor Sensor System	PC or EC	A or P
Tactile sensors (detection of physical contact or closeness; security switches)	Contact switches, bumpers Optical barriers Noncontact proximity sensors	EC EC EC	P A A
Wheel/motor sensors (wheel/motor speed and position)	Brush encoders Potentiometers Synchros, resolvers Optical encoders Magnetic encoders Inductive encoders Capacitive encoders	PC PC PC PC PC PC PC	P P A A A A A
Heading sensors (orientation of the robot in relation to a fixed reference frame)	Compass Gyroscopes Inclinometers	EC PC EC	P P A/P
Ground-based beacons (localization in a fixed reference frame)	GPS Active optical or RF beacons Active ultrasonic beacons Reflective beacons	EC EC EC EC	A A A A
Active ranging (reflectivity, time-of-flight, and geometric triangulation)	Reflectivity sensors Ultrasonic sensor Laser rangefinder Optical triangulation (1D) Structured light (2D)	EC EC EC EC EC	A A A A A
Motion/speed sensors (speed relative to fixed or moving objects)	Doppler radar Doppler sound	EC EC	A A
Vision-based sensors (visual ranging, whole-image analysis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

Characterization of sensor performance

- **Dynamic Range:** measure the ratio between the maximum and the minimum input values that can be measured by the sensor. Since the dynamic range can be very large, the ratio is usually expressed in *decibel*:

$$10 \log \left[\frac{\mathsf{maxInputValue}}{\mathsf{minInputValue}} \right] \ (\mathrm{dB})$$

وضوح

- **Resolution:** minimum difference that can be measured between two values (for digital sensors it is usually related to the A/D conversion)

- **Bandwidth or Frequency:** the (max) speed with which a sensor can provide a stream of readings, one has also to consider phase (delay) of the signal

Characterization of sensor performance

- **Sensitivity:** ratio of output change to input change, dy/dx (e.g., magnitude of change of the output of a visual sensor in relation to a change in the illumination)

- **Cross-sensitivity** (and cross-talk): sensitivity to (other) environmental parameters (e.g. temperature, magnetic field caused by ferrous materials) and/or influence exert by other active sensors. In general, sensor sensitivity is negatively affected by cross-sensitivity.

- **Error / Accuracy:** deviation between sensor's output and the true value:

$$\text{accuracy} = 1 - \left| \frac{\text{measuredValue} - \text{trueValue}}{\text{trueValue}} \right|$$

Since the true value (the "ground truth") can be hard to assess, establishing a confident characterization of sensor sensitivity can be difficult in practice

Performance in relation to the environment

- **Systematic errors:** *deterministic*, caused by factors that can (potentially) be modeled and accounted for in the equations (e.g. calibration of a laser sensor or of the distortion caused by the optics of a camera, or the unbalance between two wheels)

- **Non-systematic errors:** *non deterministic*, hard to model precisely, can be (potentially) described in probabilistic terms (e.g., slippage of wheels that cause “incorrect” encoders reading, spurious reflections from a sonar that cause wrong range measures)

- **Precision / dependability:** *reproducibility of sensor results*, related to the ratio: range/ σ between the measure range and the variance of the random errors resulting from sensor measurements

Dead reckoning sensors

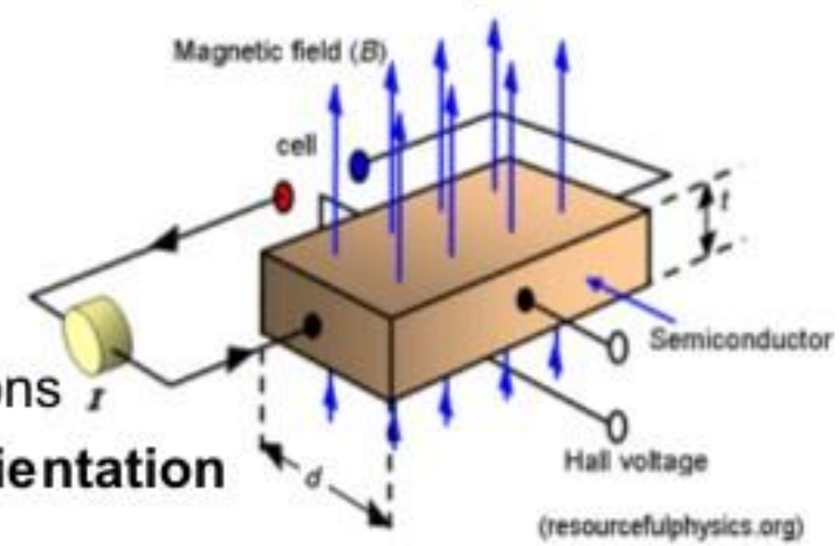
Odometry sensors: Motor Encoders, to measure wheels, rotors, helices … rotation

Inertial sensors (measure forces, non-inertial effects): Gyroscope, Accelerometer

Heading / orientation sensors: Compass, Inclinometer

Compass

- Used since before 2000 B.C.
  - when Chinese suspended a piece of natural magnetite from a silk thread and used it to guide a chariot over land.
- Magnetic field on earth
  - absolute measure for orientation (even birds use it for migrations (2001 discovery))
- Large variety of solutions to measure magnetic/true north
  - mechanical magnetic compass
  - Gyrocompass
  - direct measure of the magnetic field (Hall-effect, magneto-resistive sensors)
- Major drawback of magnetic solutions
  - weakness of the earth field (30 μTesla)
  - easily disturbed by magnetic objects or other sources
  - bandwidth limitations (0.5 Hz) and susceptible to vibrations
  - **not suitable for indoor environments for absolute orientation**
  - useful indoor (only locally)



Inclinometer

Technology for measuring *slopes*, usually based on fluids

Accelerometer

An accelerometer is a device measuring all external forces applied to it, including gravity. Conceptually an accelerometer is a *spring-mass-damper* system

In a mechanical accelerometer, a mass is attached to a spring. Assuming an ideal spring, under the influence of an external force, at equilibrium mass deflection *x* is a measure of the acceleration along spring's axis, accounting for the damping effect (coefficient *c*)

$$F_{applied} = F_{inertial} + F_{damping} + F_{spring} = m\ddot{x} + c\dot{x} + kx$$

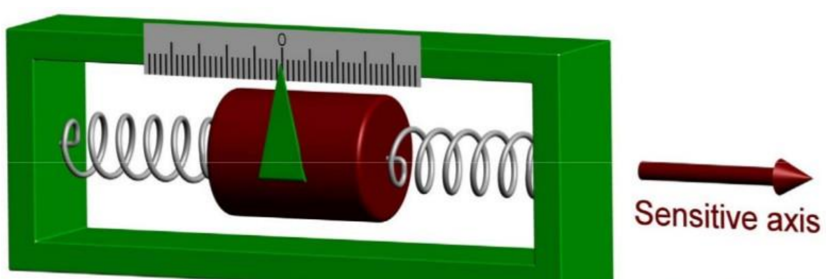
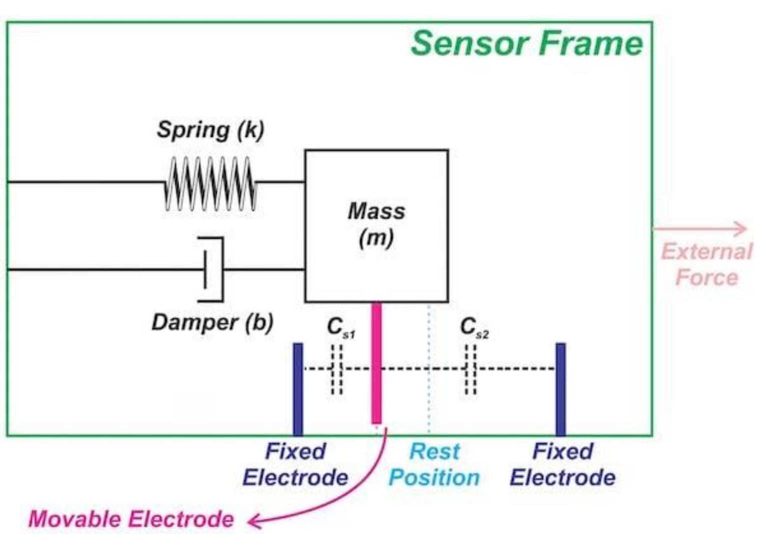


Figure: Gade (2004)

$$At\ equilibrium\ (\ddot{x} = 0),\ a_{applied} = \frac{kx}{m}$$

Mounting 3 accelerometers in 3 orthogonal directions, omnidirectional measures can be performed

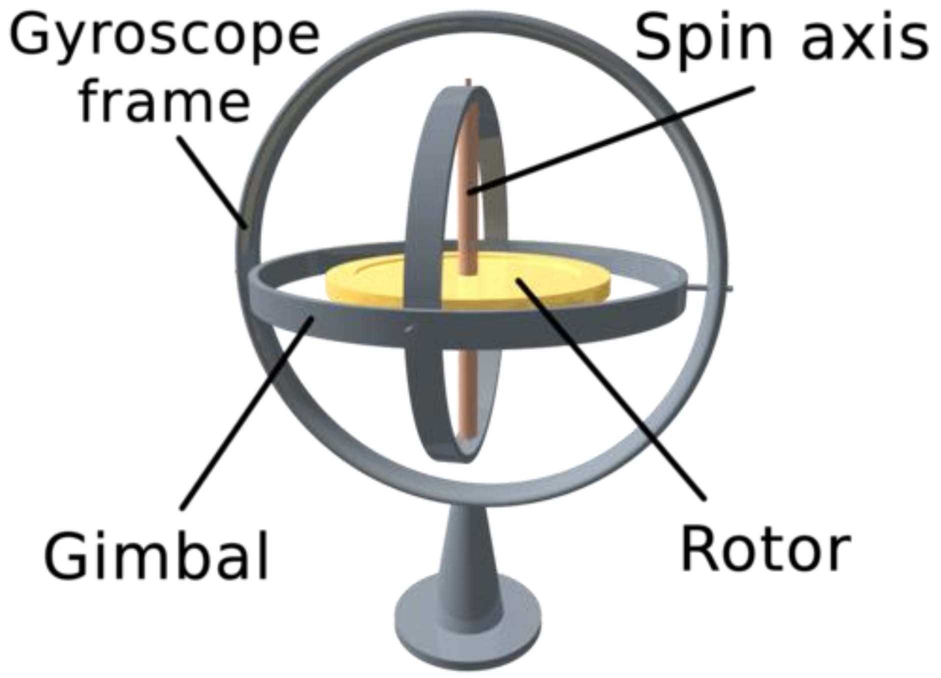


- Mechanical and capacitive accelerometers are usually *low-pass*, measuring up to 500 Hz
- Piezoelectric accelerometers can go up to 100 KHz

Gyroscope

Gyroscopes are ***heading sensors*** that preserve the orientation in relation to a fixed reference frame, allowing to measure the ***angular velocity*** ω relative to the inertial space

Maintain angular momentum (mechanical gyro). A spinning wheel will resist any change in its angular momentum vector relative to inertial space. Isolating the wheel from vehicle angular movements by means of gimbals and then output the gimbal positions is the idea of a mechanical gyro.



The angular velocity is measured around the spinning axis

Issue: friction in the bearings of the gyro axis introduce small torques, limiting long-term space stability and introducing small errors over time (e.g., 0.1 degrees / 6 hours for good, very expensive gyros 100,000 $)

Gyroscope: optical

- **The Sagnac-effect.** The inertial characteristics of light can also be utilized, by letting two beams of light travel in a loop in opposite directions. If the loop rotates clockwise, the clockwise beam must travel a longer distance before finishing the loop. The opposite is true for the counter-clockwise beam. Combining the two rays in a detector, an interference pattern is formed, which will depend on the angular velocity.

The loop can be implemented with 3 or 4 mirrors (*Ring Laser Gyro*), or with optical fibers (*Fiber Optic Gyro*).

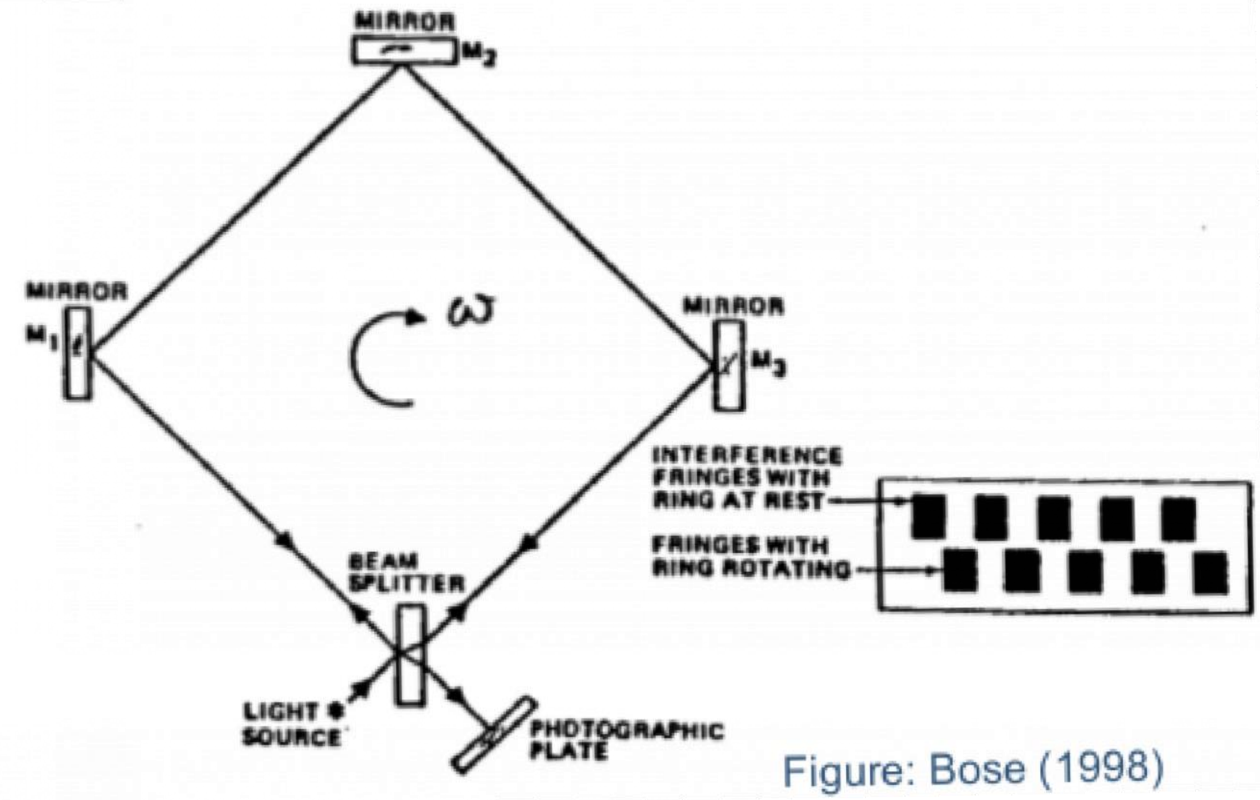


Figure: Bose (1998)

With optical gyros, bandwidth can easily be > 100 kHz, with resolution of 10^{-4} degrees/h

Inertial measurement unit (IMU)

- Multiple inertial sensors are often *assembled* together to form an **Inertial Measurement Unit (IMU)**

➡Typically the unit has 3 accelerometers and 3 gyros

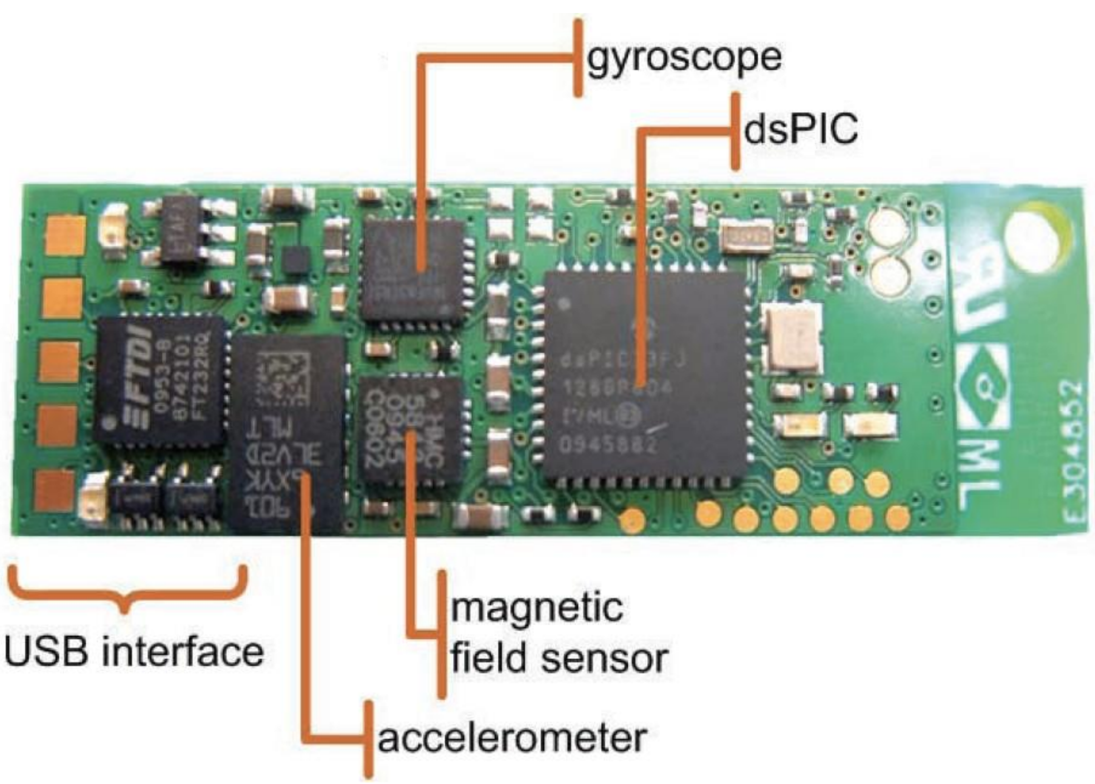
- The accelerometers are placed such that their measuring axes are orthogonal to each other.
- The gyroscopes are placed in a similar orthogonal pattern, measuring rotational position in reference to an arbitrarily chosen coordinate system
- Optionally, 3 magnetometers / compasses can be also placed

Inertial measurement unit (IMU)

The VN-100 is a miniature, high-performance Inertial Measurement Unit (IMU) and Attitude Heading Reference System (AHRS). Incorporating the latest MEMS sensor technology, the VN-100 combines 3-axis accelerometers, 3-axis gyros, 3-axis magnetometers, a barometric pressure sensor and a 32-bit processor.

Along with providing calibrated sensor measurements, the VN-100 also computes and outputs a real-time 3D orientation solution that is continuous over the complete 360 degrees of motion.

ETHZ custom design

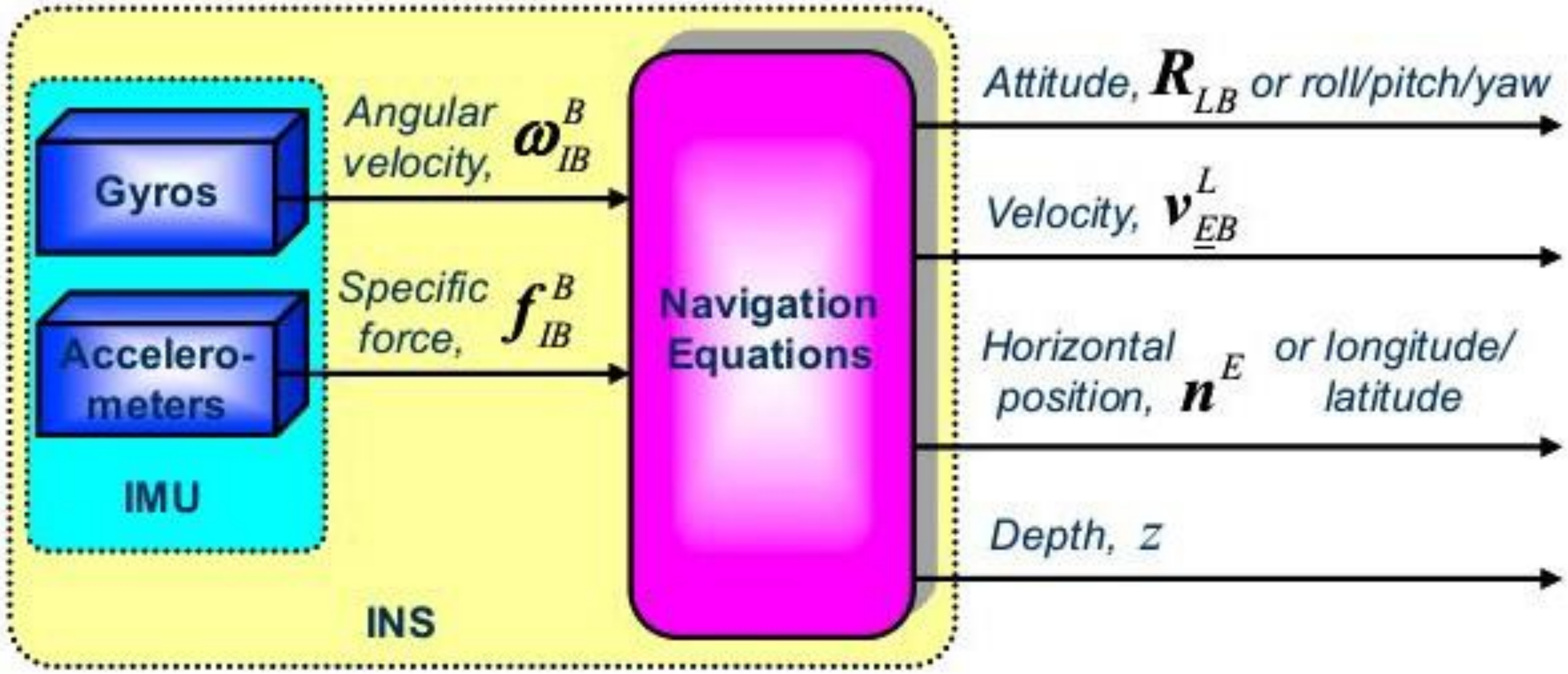


Honeywell HG1700 ("medium quality"):

- 3 accelerometers, accuracy: 1 mg
- 3 ring laser gyros, accuracy: 1 deg/h
- Rate of all 6 measurements: 100 Hz

Inertial measurement unit (IMU)

The combination of an IMU and a computer running navigation equations is called an *Inertial Navigation System (INS)*.



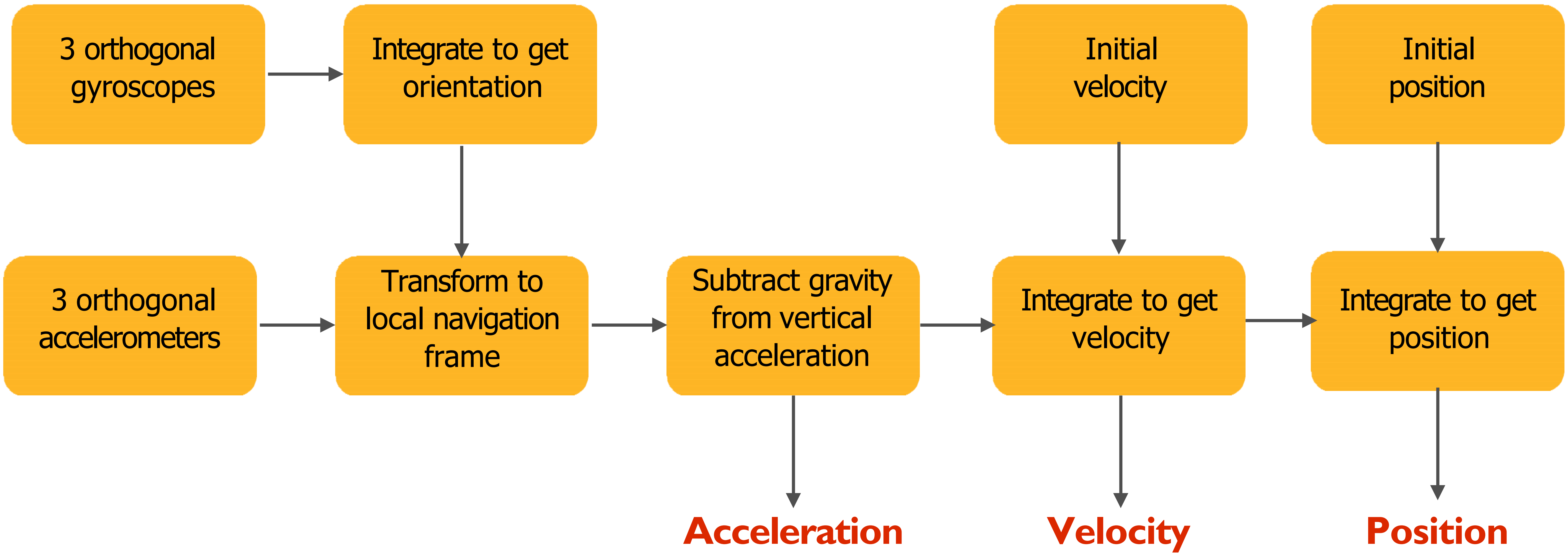
Due to errors in the gyros and accelerometers, an INS will have unlimited drift in velocity, position and attitude.

The quality of an IMU is often expressed by expected position drift per hour (1σ).

Examples (classes):

- **HG1700 is a *10 nautical miles per hour IMU.***
- **HG9900 is a *1 nautical mile per hour IMU.***

INS functional diagram



Note: The accelerometer will measure all the forces that are applied to the vehicle. Gravity will always be there. Therefore, $\boldsymbol{g}$ has to be subtracted in order to get the effective acceleration $\boldsymbol{a}$ that the vehicle is experiencing. For instance, a planar vehicle that moves straight on a road with a linearly increasing velocity $v_x = kt$, for what concerns its motion it will experience a constant acceleration $\boldsymbol{a} = (a_x, 0, 0)$. On the other hand, the measure from the accelerometer will be $\boldsymbol{a} = (a_x, 0, g)$.

Typical errors from INS (error drift)

	Accelerometer Error		Horizontal Position Error [m]			
Grade	[mg]		1s	10s	60s	1hr
Navigation	0.025		0.13 mm	12 mm	0.44 m	1.6 km
Tactical	0.3		1.5 mm	150 mm	5.3 m	19 km
Industrial	3		15 mm	1.5 m	53 m	190 km
Automotive	125		620 mm	60 m	2.2 km	7900 km

Accelerometer Misalignment		Horizontal Position Error [m]			
		1s	10s	60s	1hr
0.05°		4.3 mm	0.43 m	15 m	57 km
0.1°		8.6 mm	0.86 m	31 m	110 km
0.5°		43 mm	4.3 m	150 m	570 km
1°		86 mm	8.6 m	310 m	1100 km

	Gyro Angle Random Walk (ARW)		Horizontal Position Error [m]			
Grade	[deg/√hr]		1s	10s	60s	1hr
Navigation	0.002		0.01 mm	0.1 mm	1.3 mm	620 m
Tactical	0.07		0.1 mm	3.2 mm	46 m	22 km
Industrial	3		10 mm	0.23 m	3.3 m	1500 km
Automotive	5		20 mm	0.45 m	6.6 m	3100 km

Aided inertial navigation system

To limit the drift, an INS is usually aided by other sensors that provide direct measurements of the integrated quantities.

Examples of aiding sensors:

Sensor:	Measurement:
Pressure meter	Depth/height
Magnetic compass	Heading
Doppler velocity log	$\boldsymbol{v}^B_{\underline{E}B}$ (or $\boldsymbol{v}^B_{\underline{W}B}$, water)
Underwater transponders	Range from known position
GPS	$\boldsymbol{p}^E_{EB}$
GPS (Doppler shift)	$\boldsymbol{v}^E_{\underline{E}B}$
Multi-antenna GPS	Orientation

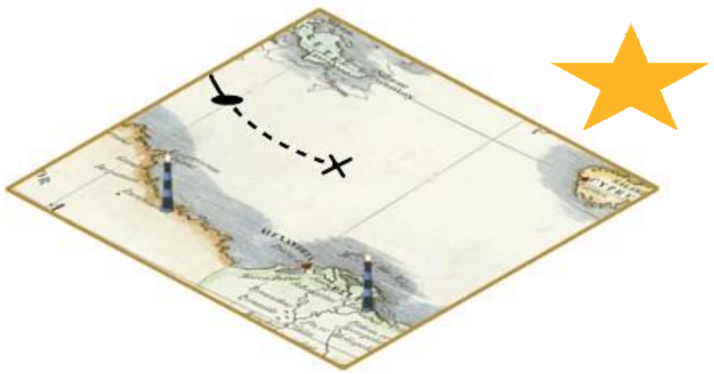
Global / map-based positioning sensors

- **Visual landmarks** (lighthouses, stars, natural landmarks)
- **Ground radio beacons** (UWB or WiFi anchors, RFID markers)
- **Satellite radio beacons** (GPS)

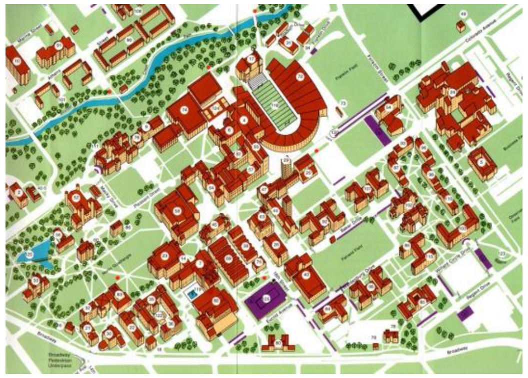
Exteroceptive sensors

Global / map-based positioning sensors

Beacon-based positioning / navigation



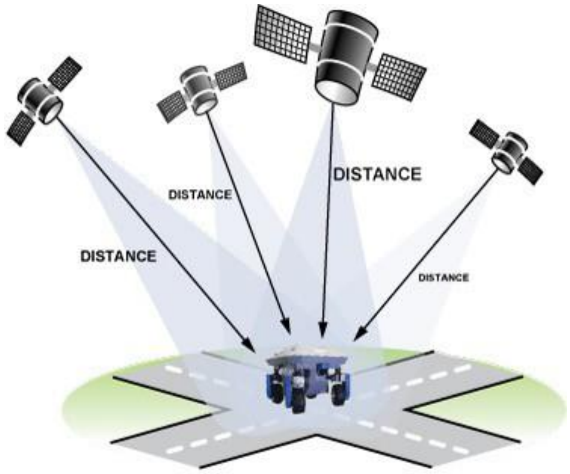
Active vs. Passive *Landmarks* in the environment



Natural vs. Artificial

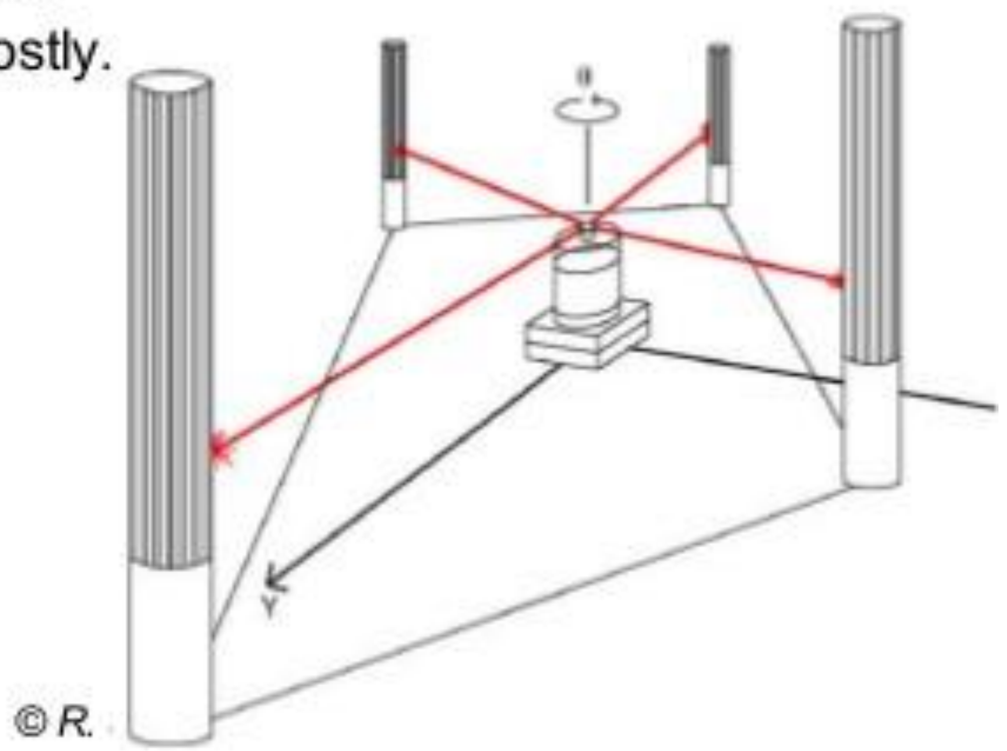
Visual vs. Acoustic vs. Radio vs. Tactile ….

Ground vs. Satellite / Aerial



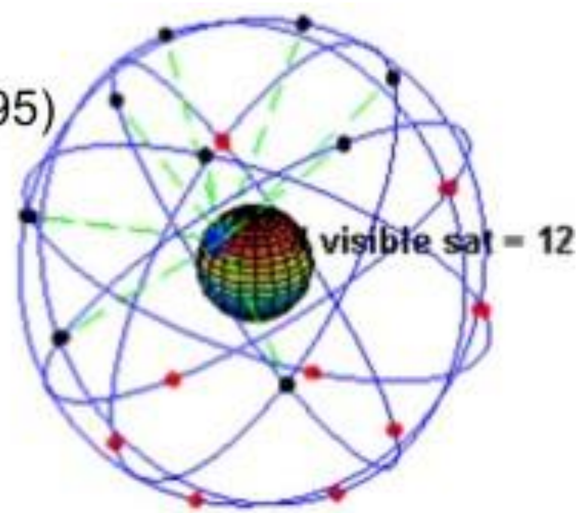
Active radio beacons

- "Elegant" way to solve the localization problem in mobile robotics
- **Beacons are signaling guiding devices with a precisely known position**
- Beacon base navigation is used since the humans started to travel
  - Natural beacons (landmarks) like **stars, mountains or the sun**
  - Artificial beacons like **lighthouses**
- The recently introduced Global Positioning System (GPS) revolutionized modern navigation technology
  - Already one of the key sensors for outdoor mobile robotics
  - For indoor robots GPS is not applicable,
- Major drawback with the use of beacons in indoor:
  - Beacons require changes in the environment -> costly.
  - Limit flexibility and adaptability to changing environments.

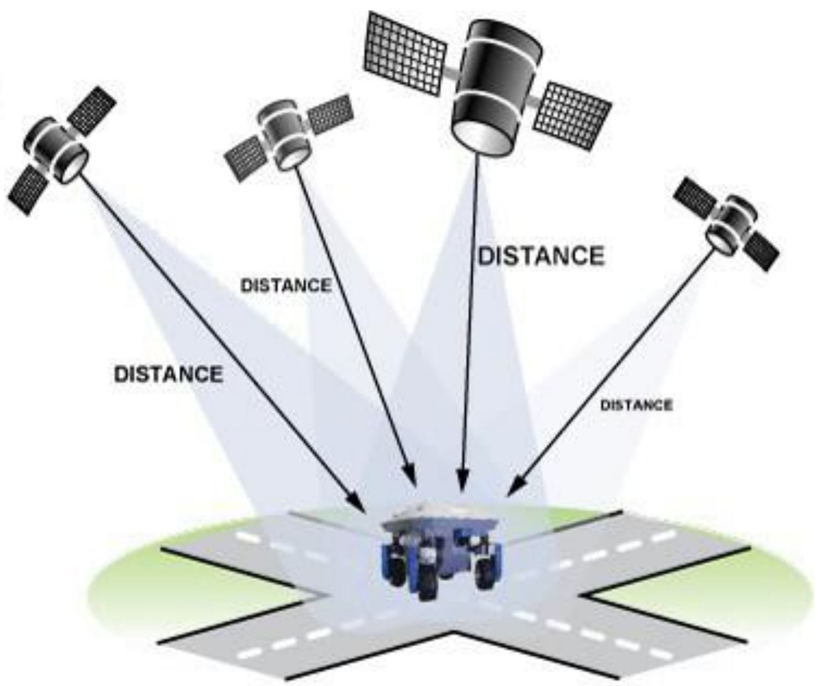


Global positioning system (GPS)

- Facts
  - Recently it became accessible for commercial applications (1995)
  - 24+ satellites orbiting the earth every 12 hours at a height of 20.190 km.
  - 4 satellites are located in each of 6 orbits with 60 degrees orientation between each other.



- Working Principle
  - Location of any GPS receiver is determined through a time of flight measurement (satellites send orbital location (*ephemeris*) plus time; the receiver computes its location through **trilateration** and **time correction**)



- Technical challenges:
  - **Time synchronization** between the individual satellites and the GPS receiver
  - Real time update of the exact location of the satellites
  - Precise measurement of the time of flight
  - **Interferences** with other signals

- All satellites broadcast in sync their position
- Different TOF due to different satellite distances from the receiver
- Trilateration of measures

Global positioning system (GPS)

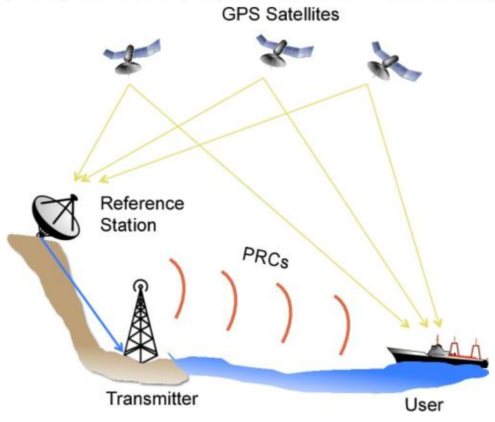
- **Time synchronization**:
  - **atomic clocks on each satellite**
  - monitoring them from different ground stations.
- Ultra-precision time synchronization is extremely important
  - electromagnetic radiation propagates at light speed
- **Light travels roughly 0.3 m per nanosecond**
  - position accuracy proportional to precision of time measurement
- **Real time update of the exact location of the satellites:**
  - monitoring the satellites from a number of widely distributed ground stations
  - master station analyses all the measurements and transmits the actual position to each of the satellites
- **Exact measurement of the time of flight**
  - the receiver correlates a pseudocode with the same code coming from the satellite
  - The delay time for best correlation represents the time of flight.
  - **quartz clock on the GPS receivers are not very precise**
  - the range measurement with four satellite allows to identify the three values (x, y, z) for the position and the clock correction ΔT

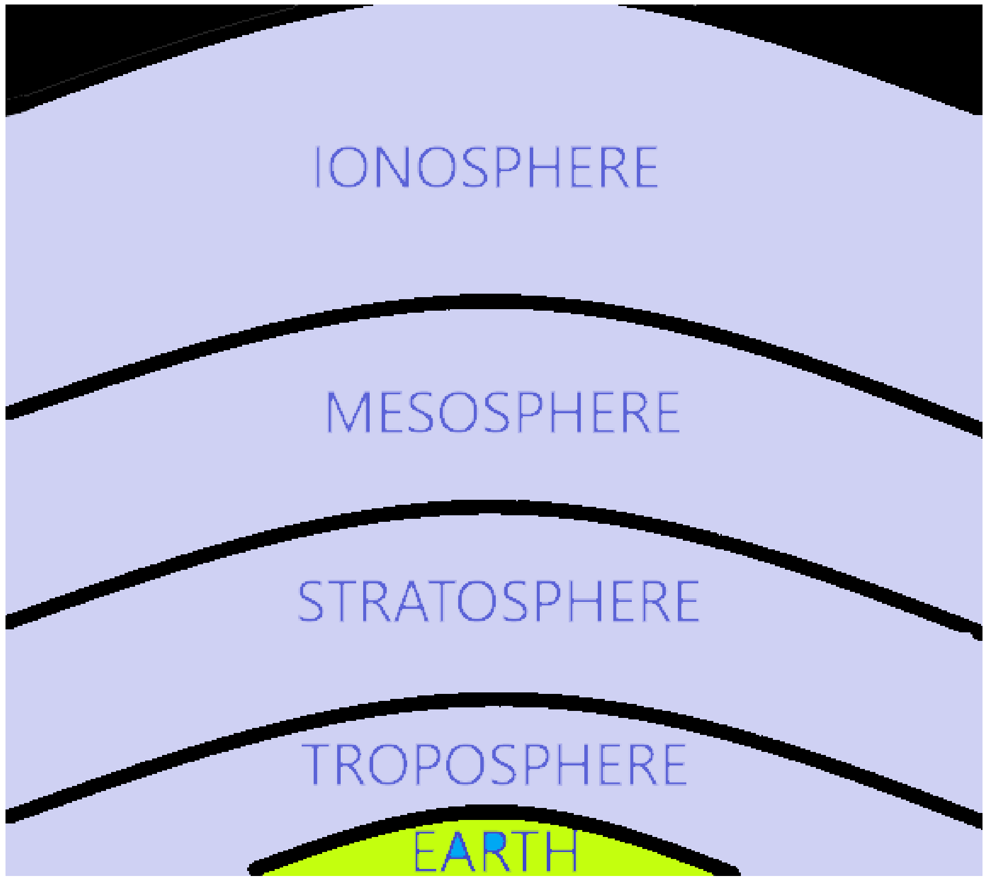
- Ionosphere and troposphere status affects TOF, hence precision
- Nominal precision: ~10 m (it can be brought to 2-3m with filtering)
- DGPS: Differential GPS, that makes use a reference station with known location
- **RTK** (Real-Time Kinematic) uses measurements of the phase of the signal's carrier wave, and relies on a reference station, providing up to **centimeter-level accuracy.**

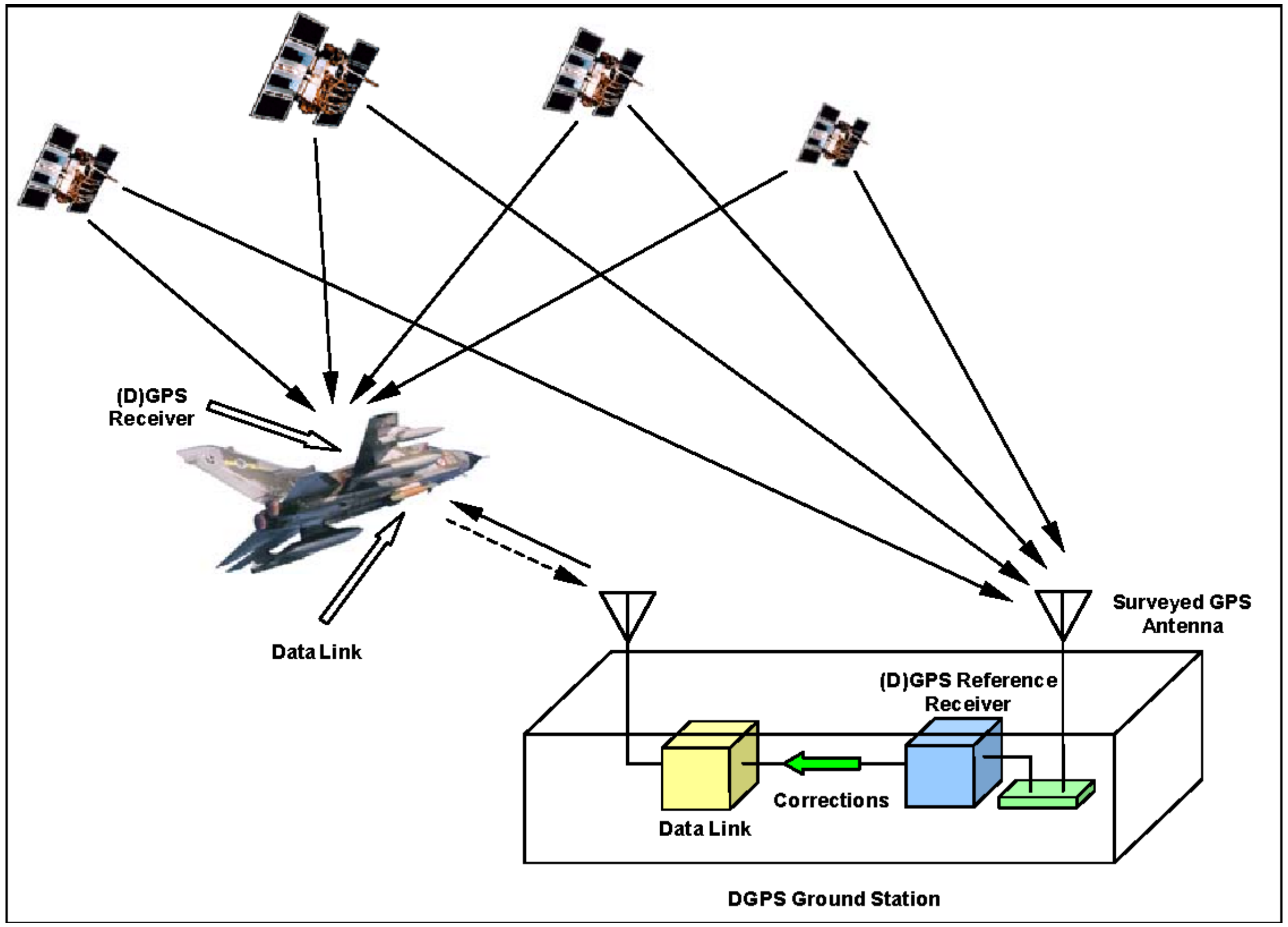
Differential GPS

- DGPS requires that a GPS receiver, known as the **base station**, be set up on a **precisely known location.** The base station receiver calculates its position based on satellite signals and compares this location to the known location. The difference is applied to the GPS data recorded by the roving GPS receiver
- **position accuracies in sub-meter to cm range**

  (RTK: DGPS with an improved version of the RTCM protocol)







Range finder sensors (for navigation)

- **Sonars:** Time-of-flight of ultrasonics waves
- **Laser range finders:** Time-of-flight of collimated electro-magnetic beams (laser)
- **Time of flight cameras** Time-of-flight of infrared collimated (laser/LED) lighting source, matrix of sensors

- **Proximity sensors:** Visible or IR light, measure reflected intensity
- **Contact sensors:** Tactile interaction, measure applied mechanical or electrical forces
- **CCD/CMOS cameras:** Measure gathered intensity of visible light, use disparity or optical flow for space-time measures

Exteroceptive sensors