Educational for Drone (eDrone)

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Educational for Drone
(eDrone)
Sensors for navigation

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Università degli Studi del Sannio

Sensors for navigation

- During flight the drone must:
  - monitor the attitude of the drone during the flight mission;
  - localize the drone during the mission;
  - detect objects along the mission path;
  - measure the drone altitude respect to the ground.

- According to that, the sensors embedded on drone are:
  - Inertial Measurement Unit (IMU);
  - Global Positioning System (GPS) or Differential GPS;
  - Light Detection and Ranging (LiDAR);
  - Ultrasonic sensor;
  - Barometer

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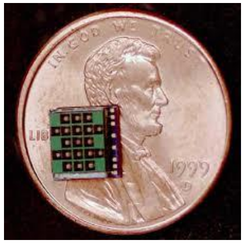
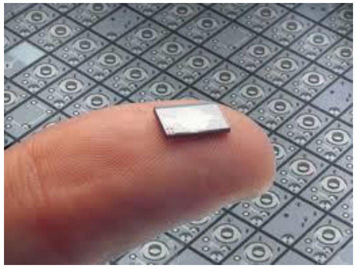
MEMS technology

- MicroElectroMechanical Systems (MEMS) are sensors or actuators that contain microelectronics and micromechanical structures.
- MEMS are fabricated using techniques similar to those used for integrated circuits. They are micrometer sized mechanical structures, such as cantilevers (e.g. capacitive accelerometer), combs, membranes and channels, that are often integrated with logic circuitry.
- The MEMS technology is used in sensor development, especially for accelerometers, gyroscopes and magnetometers design.
- MEMS advantages: ultra-small size, low power, low cost, high performance





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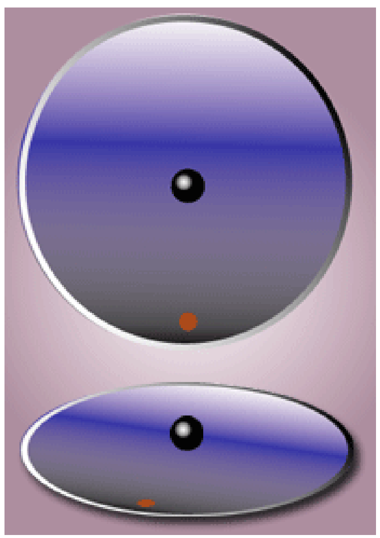
MEMS Gyroscope

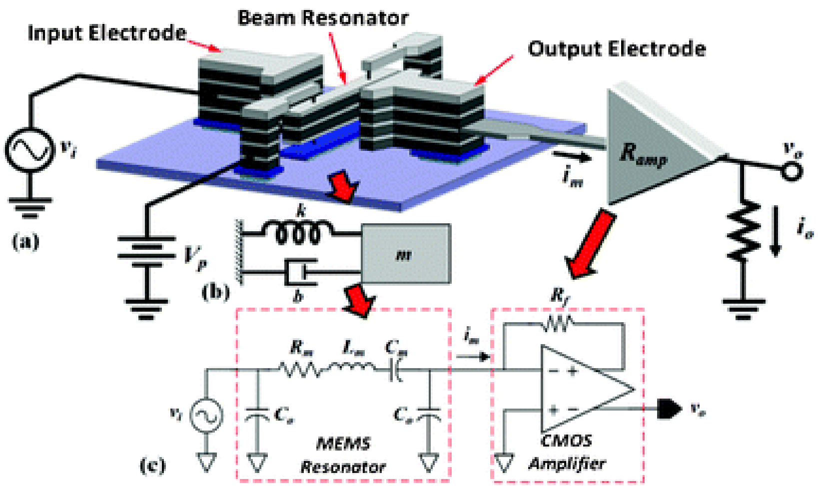
Coriolis Force



The Coriolis force is an inertial force that acts on objects that are in motion relative to a rotating reference frame. In a reference frame with clockwise rotation, the force acts to the left of the motion of the object. In one with anticlockwise (or counterclockwise) rotation, the force acts to the right. Deflection of an object due to the Coriolis force is called the Coriolis effect.

Gyroscopes – MEMS gyros:

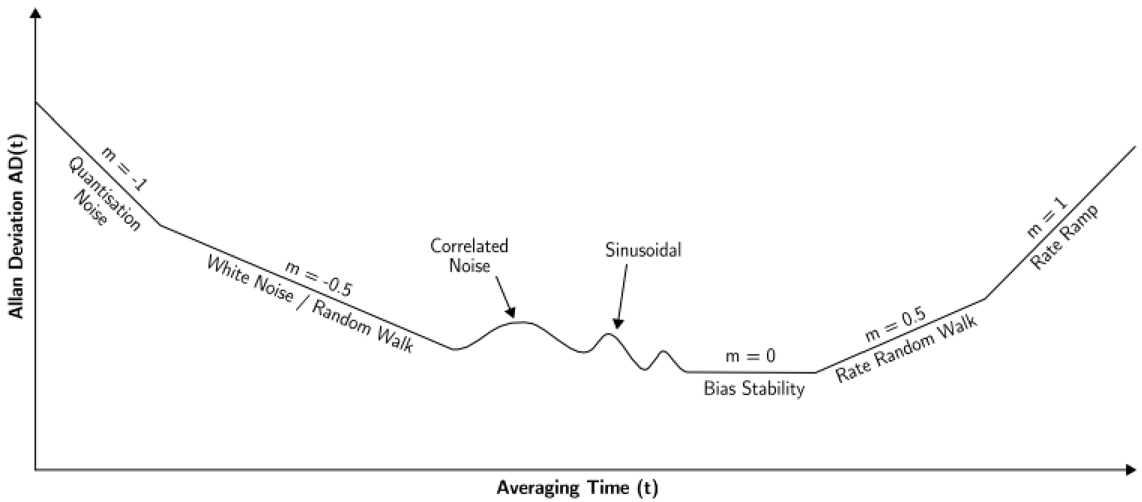
- Usually the sensing forks are coupled to a similar fork which produces the rate output signal:



- The piezo-electric drive tines are oscillated at precise amplitudes. In the presence of the angular velocity, the tines of the pick up fork move up and down out of the plane of the fork assembly. An electrical output signal is then produced by the pick up amplifier which is proportional to the input angular rate.

Gyroscopes – error Terms

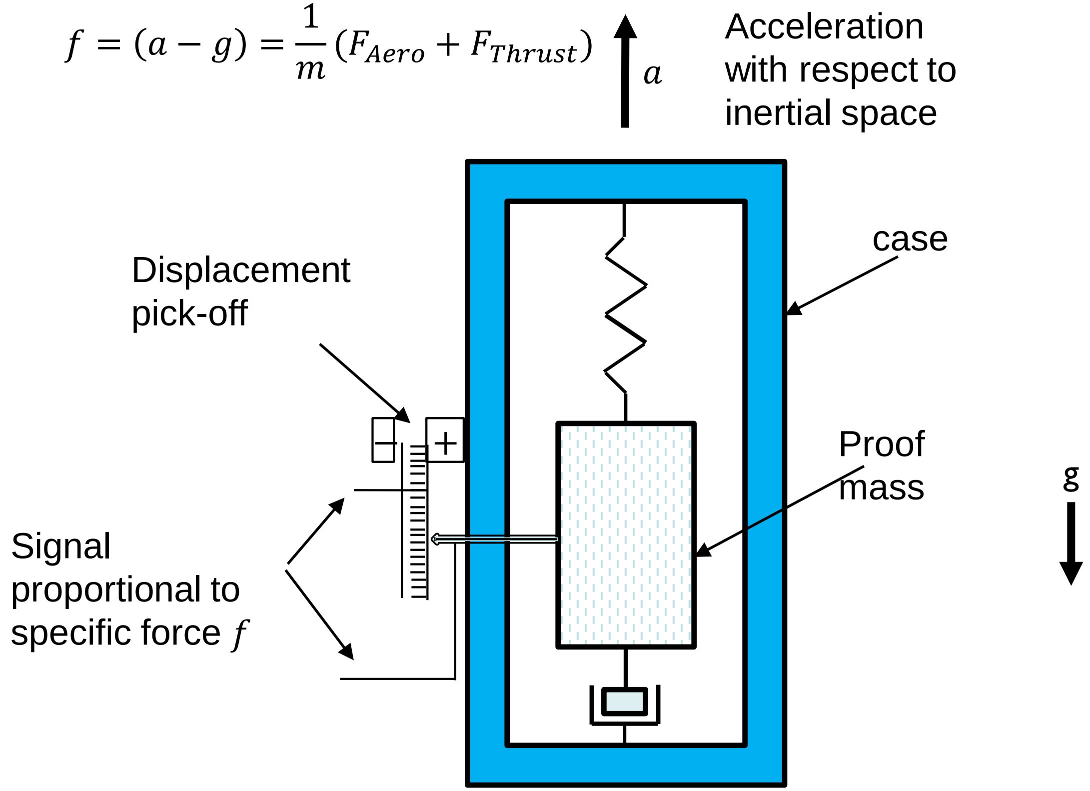
- Allan variance method is plotted as a function of the averaging period T on a log-log scale
- Different random process usually appear in different region of T:



Accelerometers - Concept

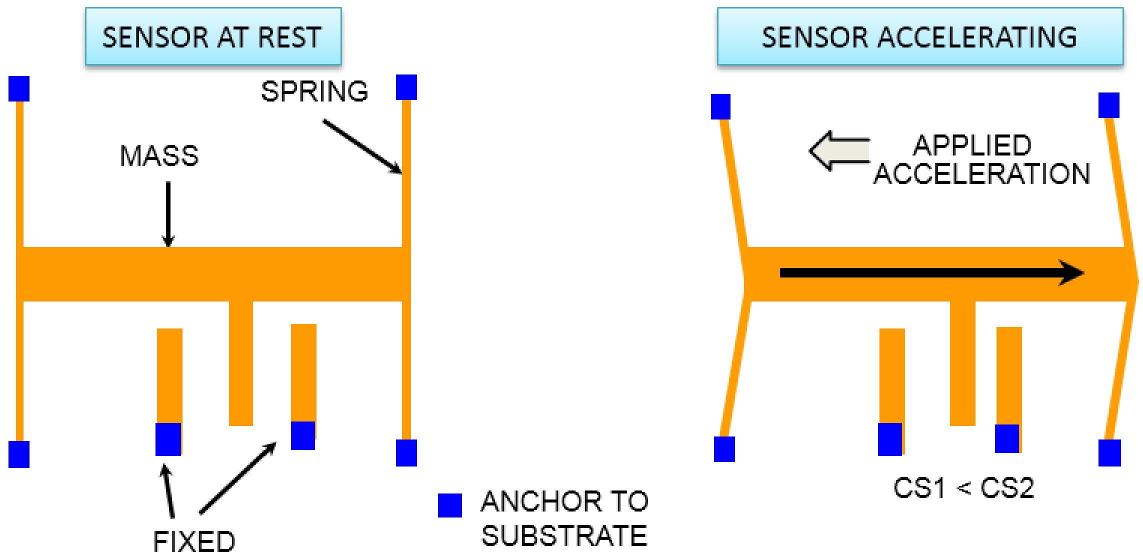
- Accelerometers measure specific force

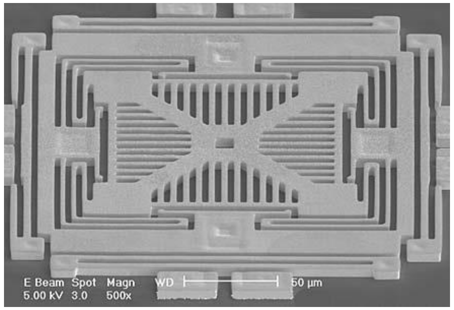
$$f = (a - g) = \frac{1}{m}(F_{Aero} + F_{Thrust})$$

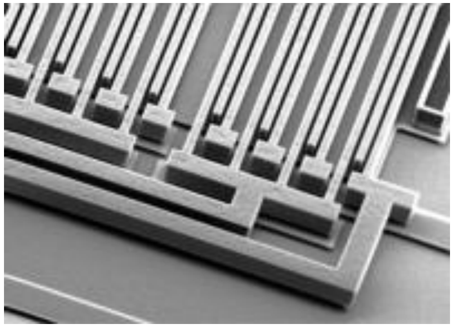


Accelerometers – MEMS sensors

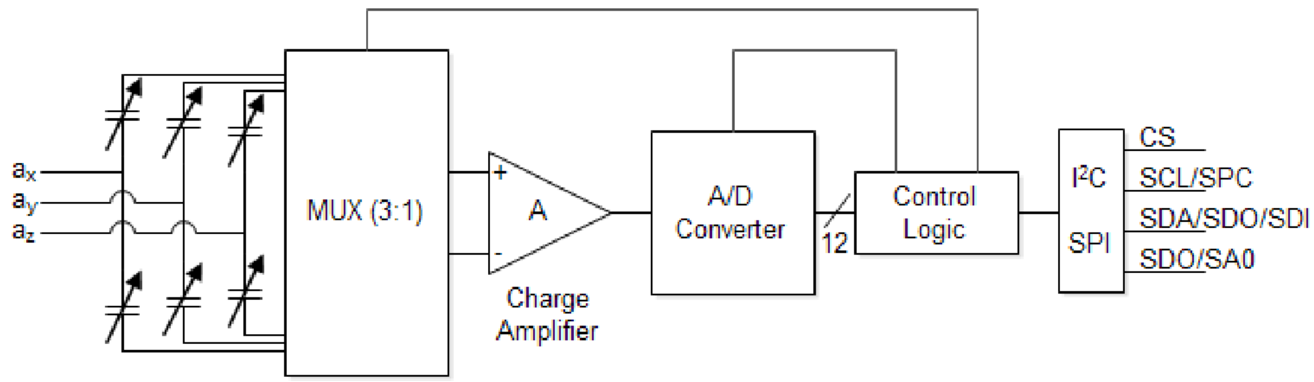
- Spring and mass from Silicon
- Change in the displacement causes an output voltage due to the change in capacitance







LIS331DLH accelerometer



It consists of:

- the capacitive sensing, which converts the acceleration on the three axes in variations of six capacities;
- the analog multiplexer (MUX) selects the component for the A/D conversion;
- the charge amplifier, converting the capacity charge to a voltage;
- the 12 bit A/D converter,
- the control logic manages the ADC and the MUX;
- the I2C/SPI digital interfaces.

Gyroscopes and accelerometer – calibration

- Calibration of the sensor suite is accomplished on temperature- controlled precise turn-tables to determine the sensors bias, scale factor, misalignment factors, g-sensitivity factors, etc:
- For gyroscopes:

$$\omega_x = B_{Gx} + S_{xx}(T)O_{gx} + S_{xy}O_{gy} + S_{xz}O_{gz} + S_{Gxx}O_{ax} + S_{Gxy}O_{ay} + S_{Gxz}O_{az}$$

$$\omega_y = B_{Gy} + S_{yx}O_{gx} + S_{yy}(T)O_{gy} + S_{yz}O_{gz} + S_{Gyx}O_{ax} + S_{Gyy}O_{ay} + S_{Gyz}O_{az}$$

$$\omega_z = B_{Gz} + S_{zx}O_{gx} + S_{zy}O_{gy} + S_{zz}(T)O_{gz} + S_{Gzx}O_{ax} + S_{Gzy}O_{ay} + S_{Gzz}O_{az}$$

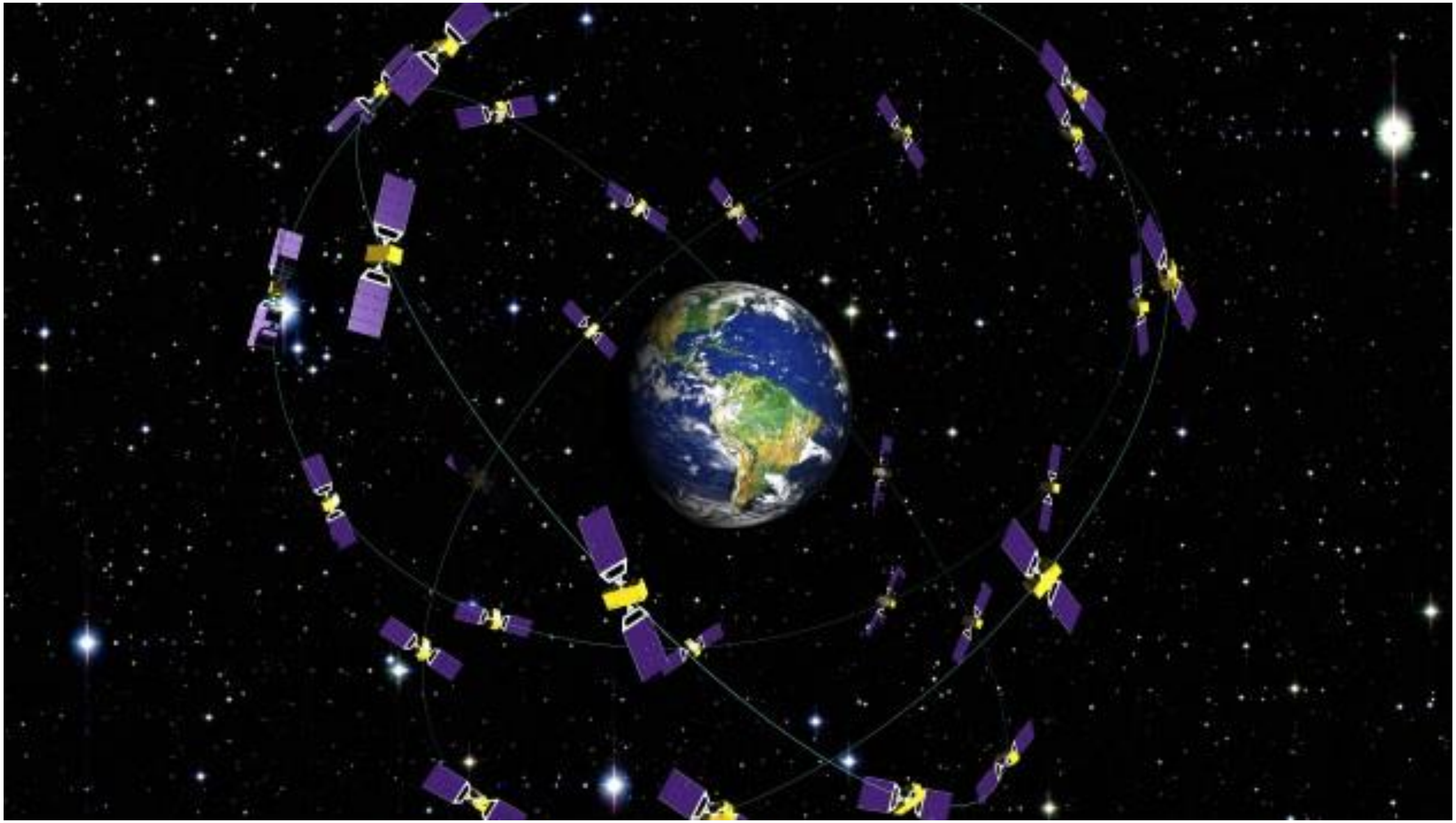
- For accelerometer:

$$a_x = B_{Ax} + S'_{xx}(T)O_{Ax} + S'_{xy}O_{Ay} + S'_{xz}O_{Az}$$

$$a_y = B_{Ay} + S'_{yx}(T)O_{Ax} + S'_{yy}O_{Ay} + S'_{yz}O_{Az}$$

$$a_z = B_{Az} + S'_{zx}(T)O_{Ax} + S'_{zy}O_{Ay} + S'_{zz}O_{Az}$$

Global navigation satellite system (GNSS)



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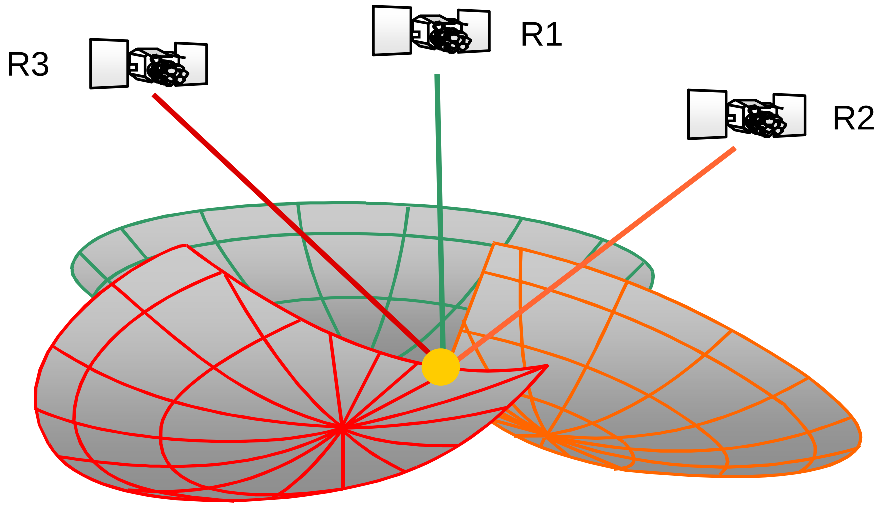
GNSS constellations

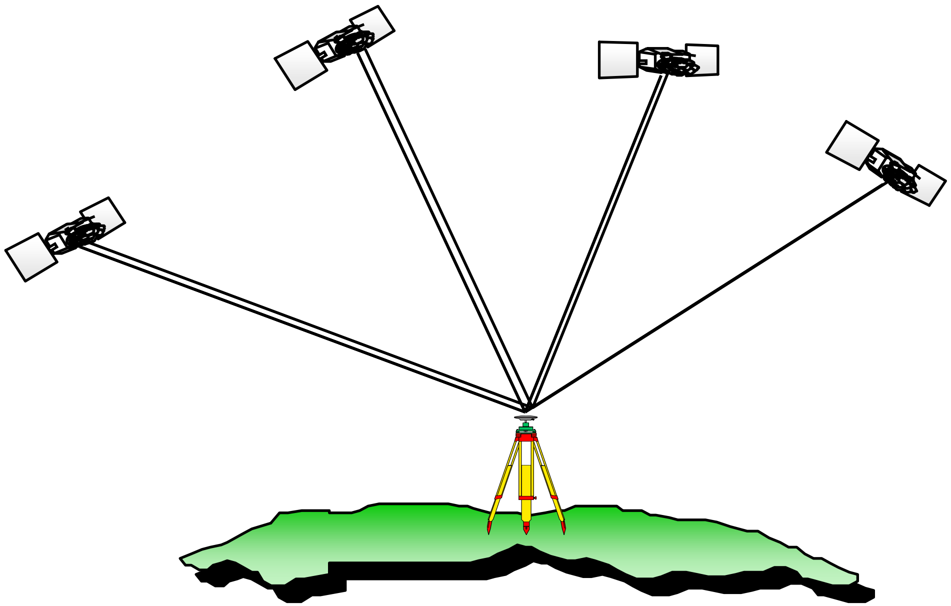
- **GPS (United States):** GPS was the first GNSS system. GPS was launched in the late 1970s by the United States Department of Defense. It uses a constellation of 27 satellites, and provides global coverage.
- **GLONASS (Russia):** GLONASS is operated by the Russian government. The GLONASS constellation consists of 24 satellites and provides global coverage.
- **Galileo (European Union):** Galileo is a civil GNSS system operated by the European Global Navigation Satellite Systems Agency (GSA). Galileo will use 27 satellites with the first Full Operational Capability (FOC) satellites being launched in 2014. The full constellation is planned to be deployed by 2020.
- **BeiDou (China):** BeiDou is the Chinese navigation satellite system. The system will consist of 35 satellites. A regional service became operational in December of 2012. BeiDou will be extended to provide global coverage by end of 2020.
- **IRNSS (India):** The Indian Regional Navigation Satellite System (IRNSS) provides service to India and the surrounding area. The full constellation of seven satellites is planned to be deployed by 2015.
- **QZSS (Japan):** QZSS is a regional navigation satellite system that provides service to Japan and the Asia-Oceania region. The QZSS system is planned to be deployed by 2018.

GNSS Principle: Point Positioning



- 3 Spheres intersect at a point
- 3 Ranges to resolve for Latitude, Longitude and Height

Point Positioning

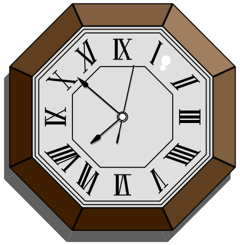


4 Ranges to resolve for Latitude, Longitude, Height & Time

It is similar in principle to a resection problem

Satellite Errors

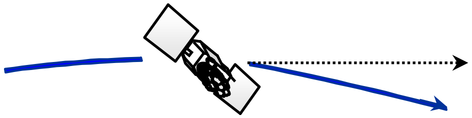
- Satellite Clock Model



though they use atomic clocks, they are still subject to small inaccuracies in their time keeping

These inaccuracies will translate into positional errors.

- Orbit Uncertainty



The satellites position in space is also important as it's the beginning for all calculations

They drift slightly from their predicted orbit

Observation Errors

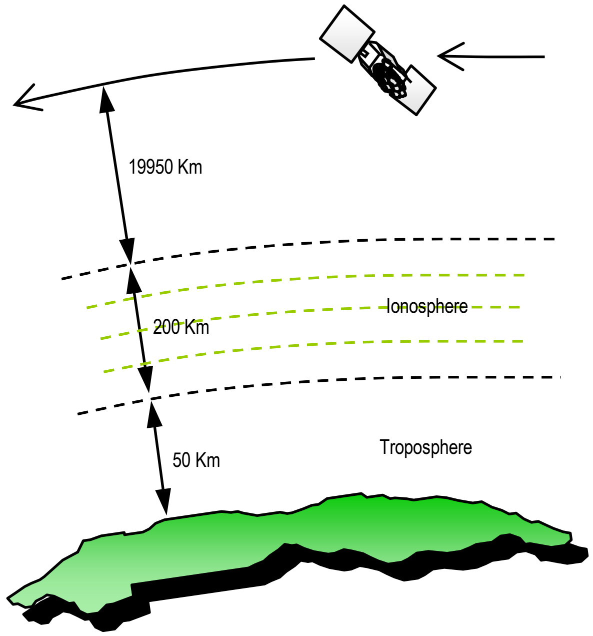
GNSS signals transmit their timing information via radio waves

It is assumed that a radio wave travels at the speed of light.

GNSS signals must travel through a number of layers making up the atmosphere.

As they travel through these layers the signal gets delayed

This delay translates into an error in the calculation of the distance between the satellite and the receiver

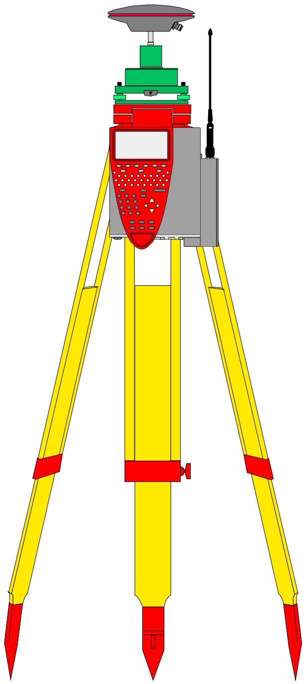


Receiver Error

Unfortunately not all the receivers are perfect. They can introduce errors of their own

Internal receiver noise

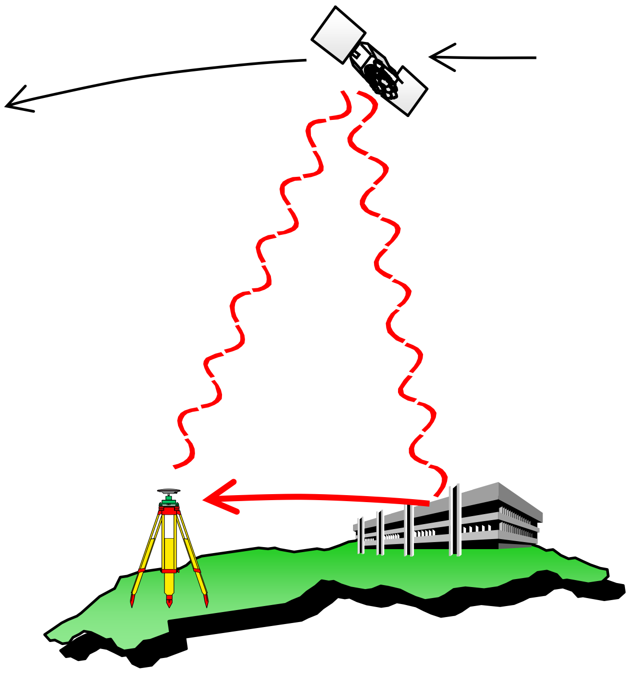
Receiver clock drift



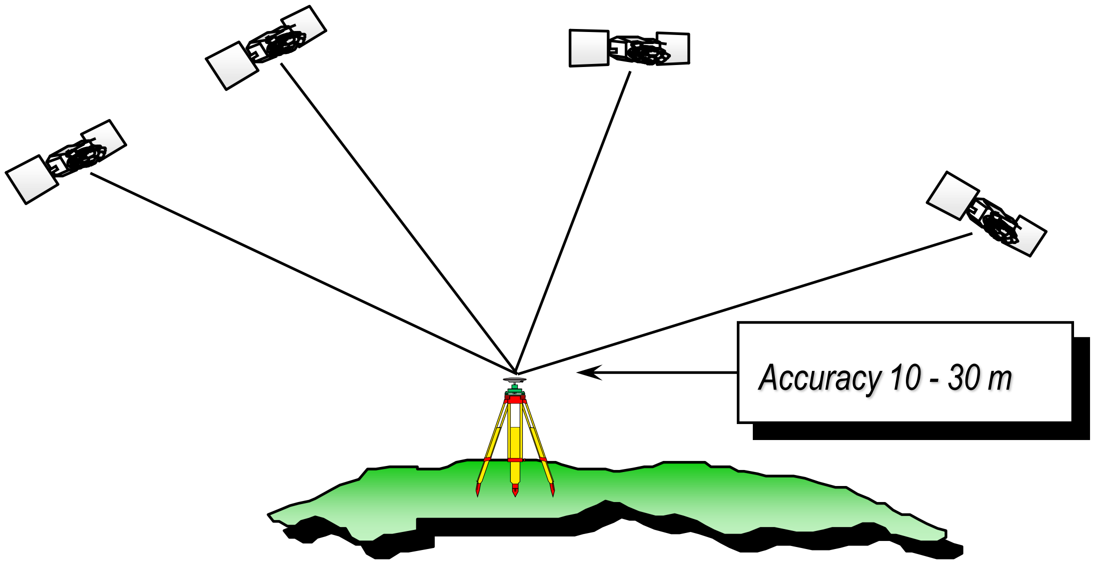
Multipath Error

- When the GPS signal arrives at earth it may reflect off various obstructions

- First the antenna receives the signal by the direct route and then the reflected signal arrives a little later



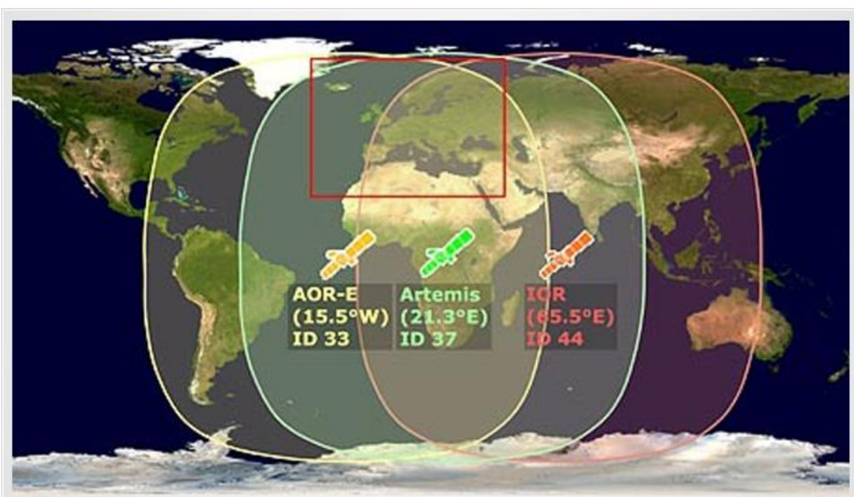
Point Positioning Accuracy

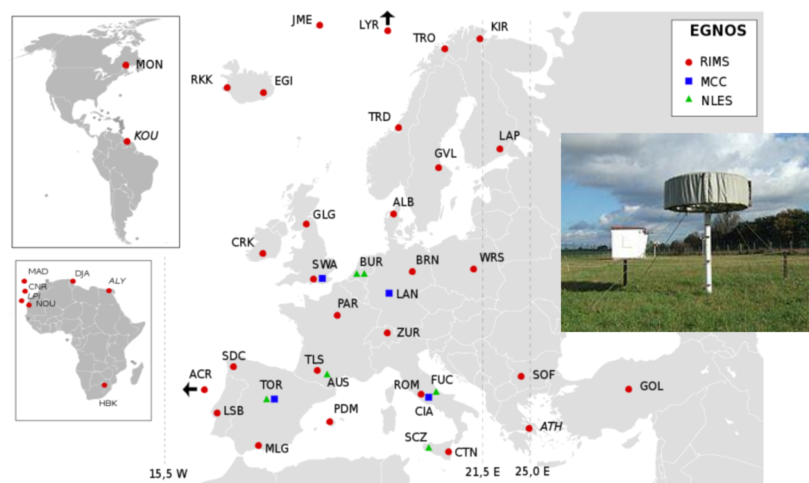


In theory a point position can be accurate to 10 – 30 m

Satellite-based augmentation systems (SBAS)

- A SBAS system is composed by a constellation of geostationary satellites with the aim of sending differential corrections, evaluated by a network of permanent terrestrial stations, such to increase the positioning accuracy achievable by GPS satellites.
- In Europe, the EGNOS (European Geostationary Navigation Overlay System) is available, composed by 3 geostationary satellites.





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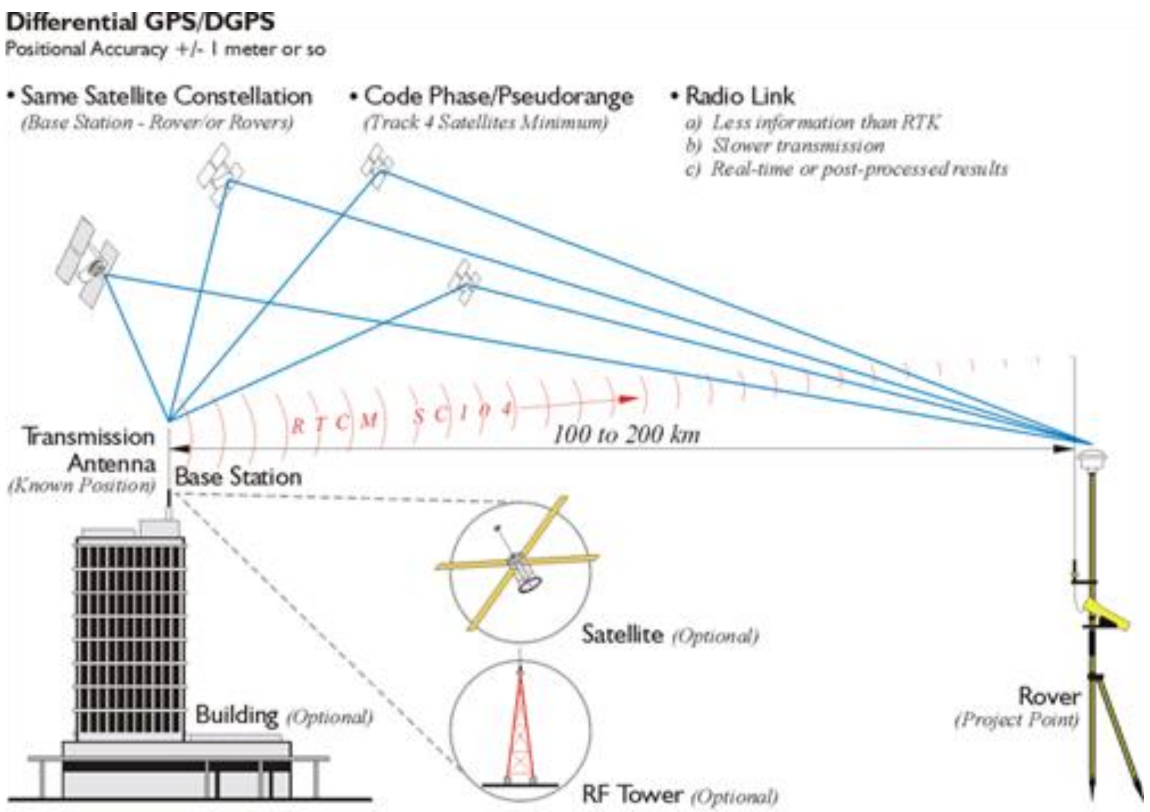
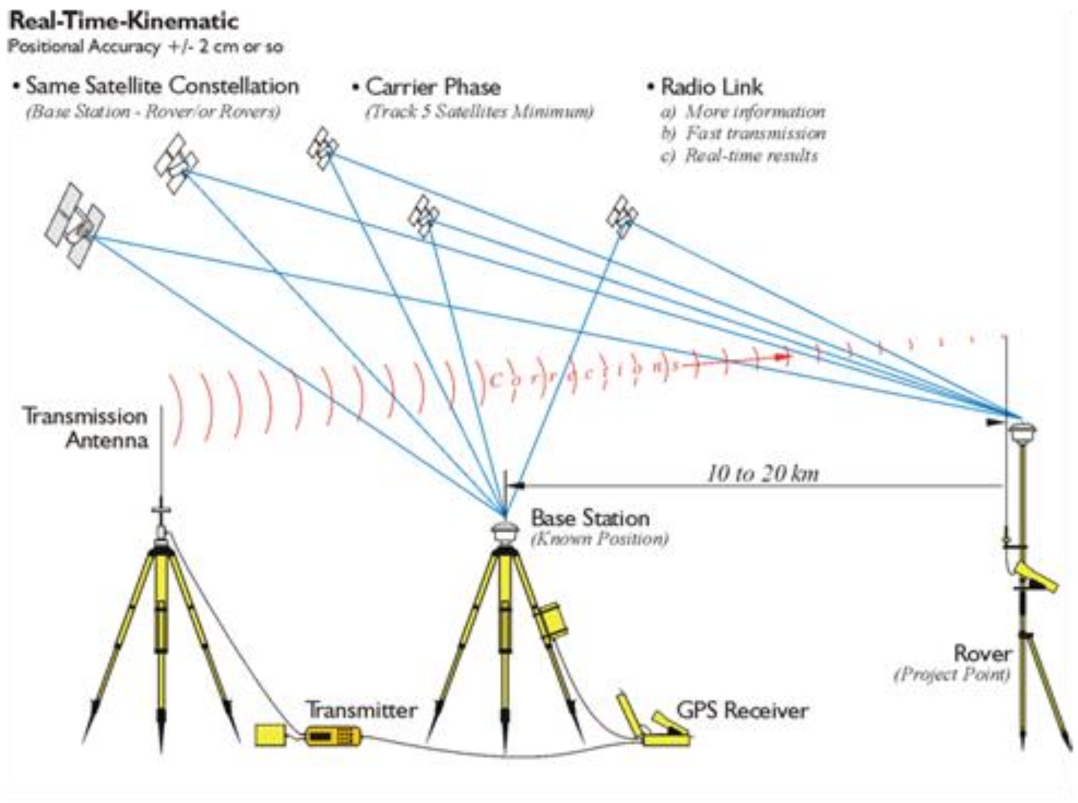
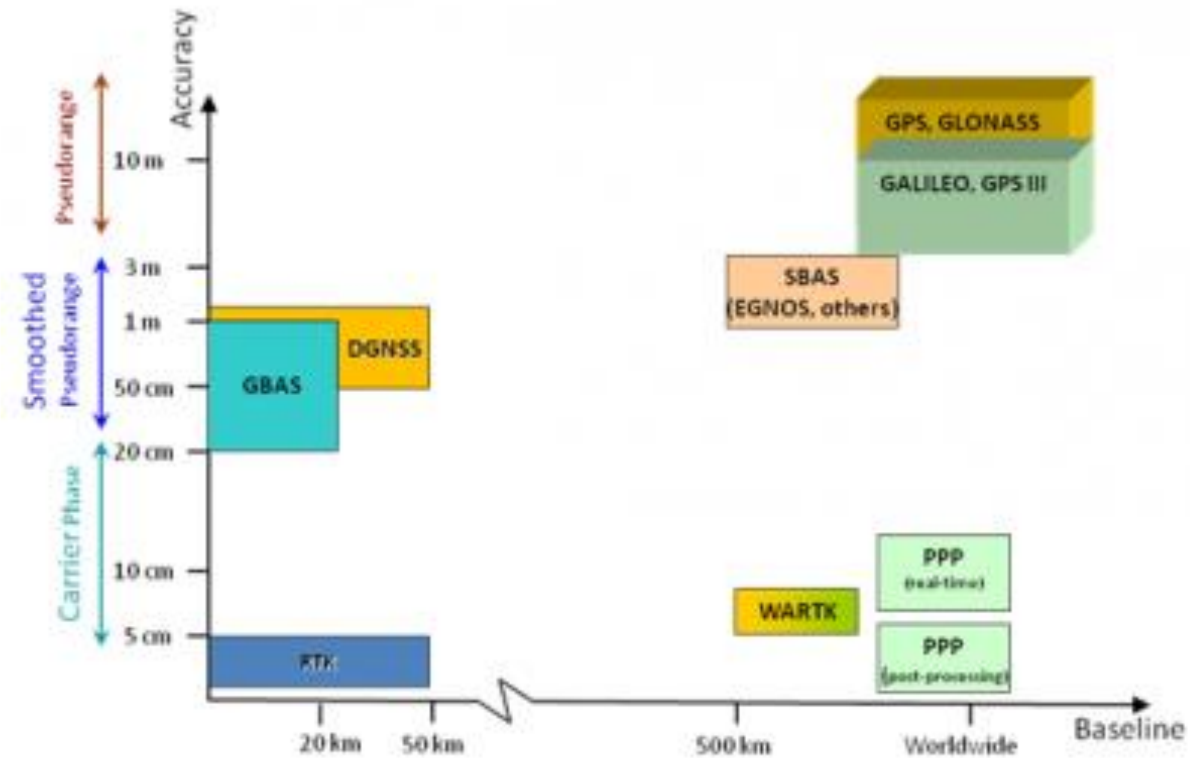
Differential GPS



Real-time kinematic



Comparison of GNSS systems



Light Detection and Ranging (LiDAR)

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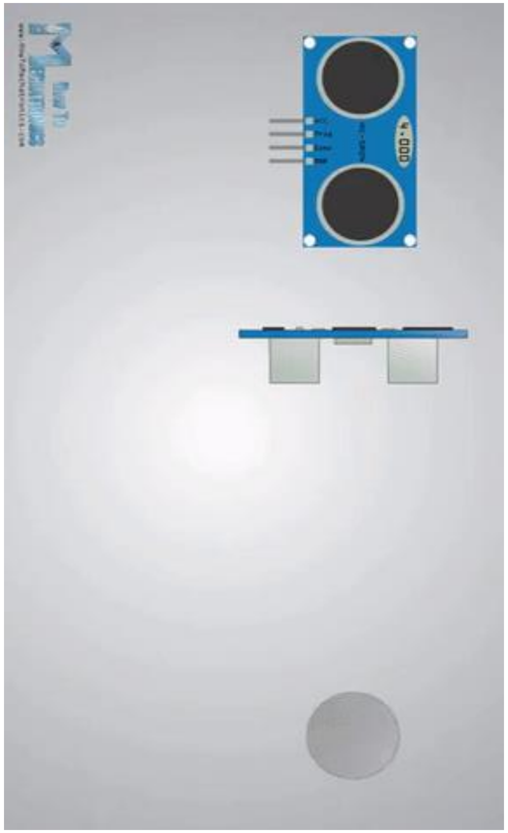
SONAR

- Ultrasonic waves transmitted to ground, reflection time determines altitude

Disadvantages:

- Atmosphere effects
- Low measurement range
- Low accuracy

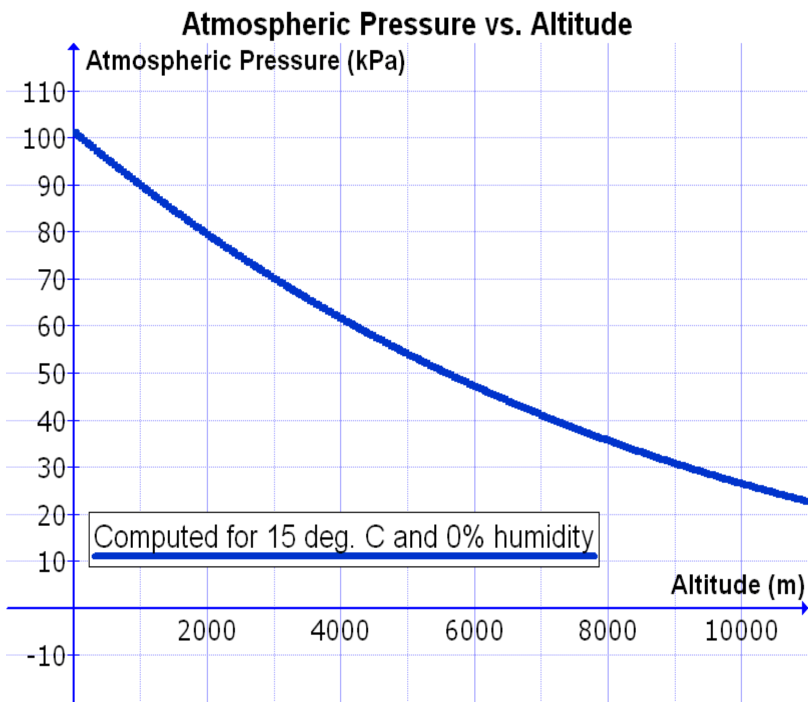


Barometer

Measures altitude by measuring *air pressure*
Relationship between altitude & air pressure

Advantages:
- Cheap
- Ease of implementation

Drawbacks:
- Recalibration with varying temperature
- Low accuracy



Inertial navigation (1/3)

- **An inertial navigation system (INS) uses the output of inertial sensors to estimate the vehicle's position, velocity, and attitude.**
- Automotive-grade micro electro-mechanical system (MEMS) inertial sensors are most suitable for low-cost UAV applications; however, when operating as a stand-alone navigator, these sensors produce positioning errors on the order of several hundreds of meter per minute. These large errors in the position, velocity, and attitude estimates are mainly due to sensor bias and noise that corrupt the measurements.
- The position error grows linearly with the initial velocity error estimate, quadratically with uncorrected bias, and at a cubic rate with attitude error.
- Despite the unbounded growth of the error with time, one of the important advantages of inertial navigators is that they are self-contained; that is, they require no external signal to provide a navigation solution.

Inertial navigation (2/3)

- Attitude determination is an integral part of INS
- Attitude can be equivalently described by a set of three angles known as the Euler angle sequence or the four-parameter attitude quaternion.
- An Euler angle sequence consists of the yaw (ψ), pitch (θ), and roll (ϕ) angles that describe three successive rotations about the body *z, y, and x* axes, respectively. Although this representation carries physical interpretation, it is singular at $\theta = \pm 90^\circ$.
- The attitude quaternion is a set of four numbers that can be related to the roll, pitch, and yaw angles using the following relationship:

$$\phi = \arctan\left(\frac{2q_2q_3 + 2q_0q_1}{2q_0^2 + 2q_3^2 - 1}\right)$$

$$\theta = \arcsin\left(-2q_1q_3 + 2q_0q_2\right)$$

$$\psi = \arctan\left(\frac{2q_2q_3 + 2q_0q_1}{2q_0^2 + 2q_3^2 - 1}\right)$$

Inertial navigation (3/3)

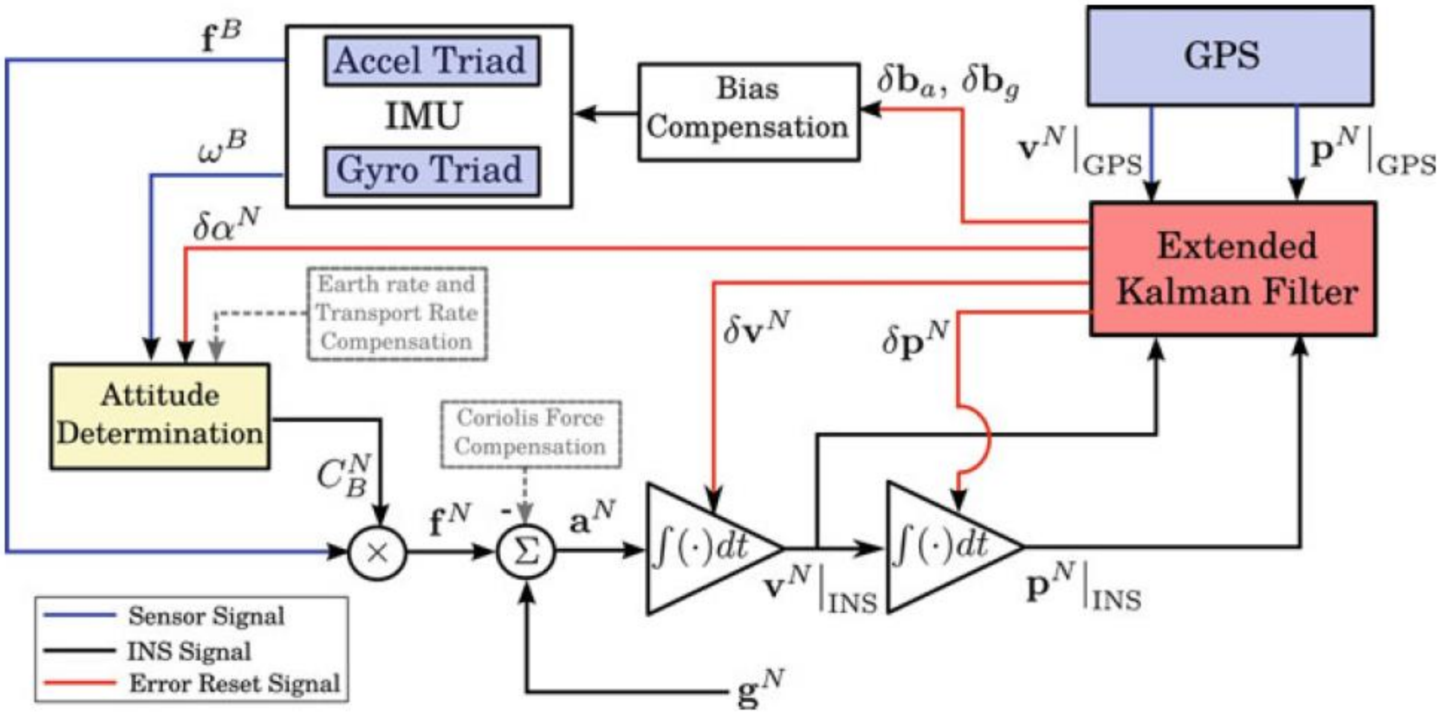
For Euler angle representation:

$$\begin{bmatrix} \phi[k+1] \\ \theta[k+1] \\ \psi[k+1] \end{bmatrix} = \begin{bmatrix} 1 & \sin(\phi[k])\tan(\theta[k]) & \cos(\phi[k])\tan(\theta[k]) \\ 0 & \cos(\phi[k]) & -\sin(\phi[k]) \\ 0 & \sin(\phi[k])\sec(\theta[k]) & \cos(\phi[k])\sec(\theta[k]) \end{bmatrix} \begin{bmatrix} \omega_x^B[k]\Delta t \\ \omega_y^B[k]\Delta t \\ \omega_z^B[k]\Delta t \end{bmatrix}$$

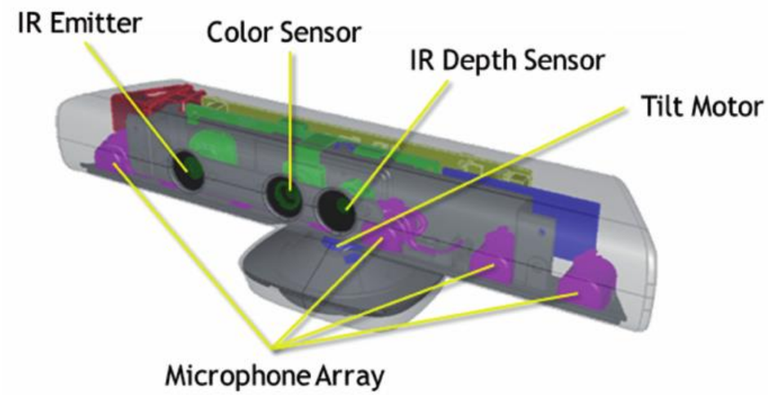
For quaternion representation:

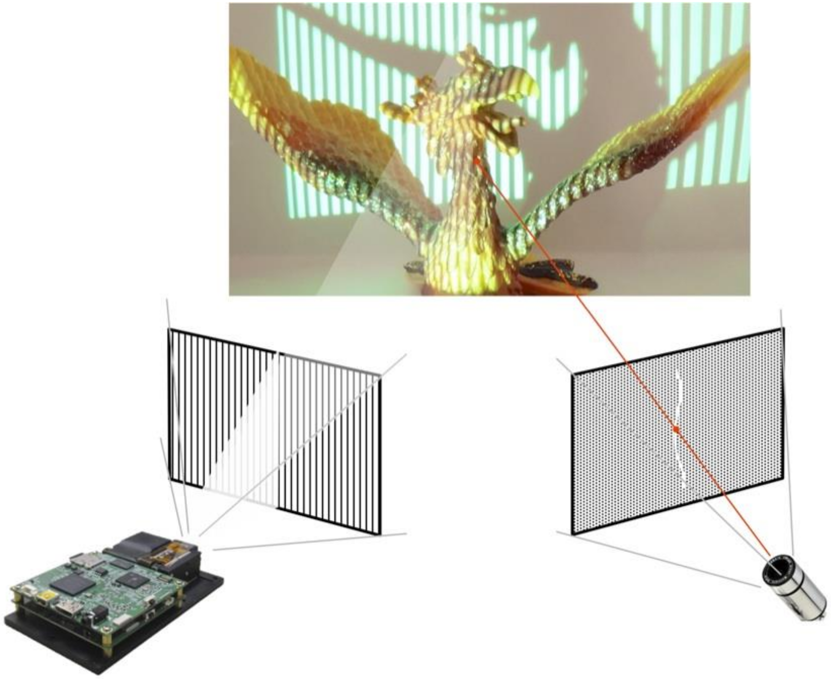
$$\mathbf{q}[k+1] = \mathbf{q}[k] \otimes \left[\, 1 \;\; \tfrac{1}{2}\omega_x[k]^B\Delta t \;\; \tfrac{1}{2}\omega_y[k]^B\Delta t \;\; \tfrac{1}{2}\omega_z[k]^B\Delta t \,\right]$$

GNSS/INS integration



Structured light sensors





TIME-of-flight cameras

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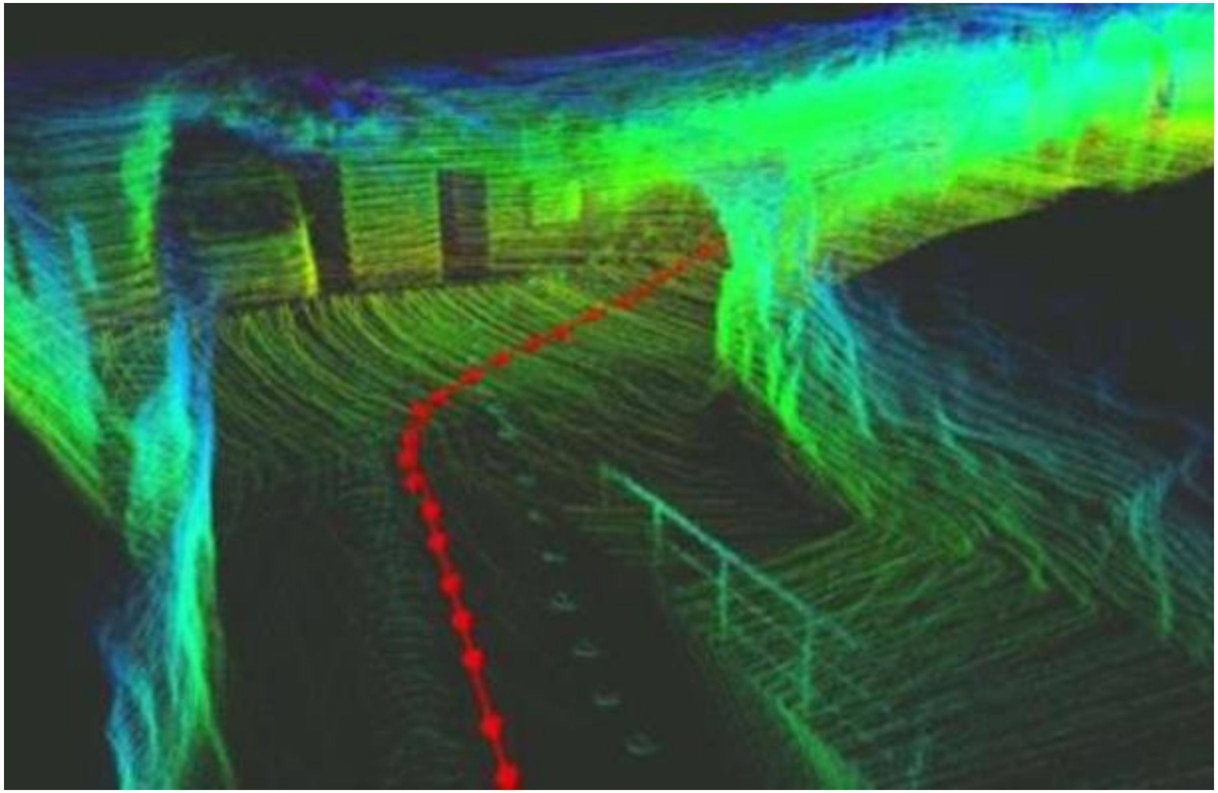
Simultaneous Localization And Mapping (SLAM)



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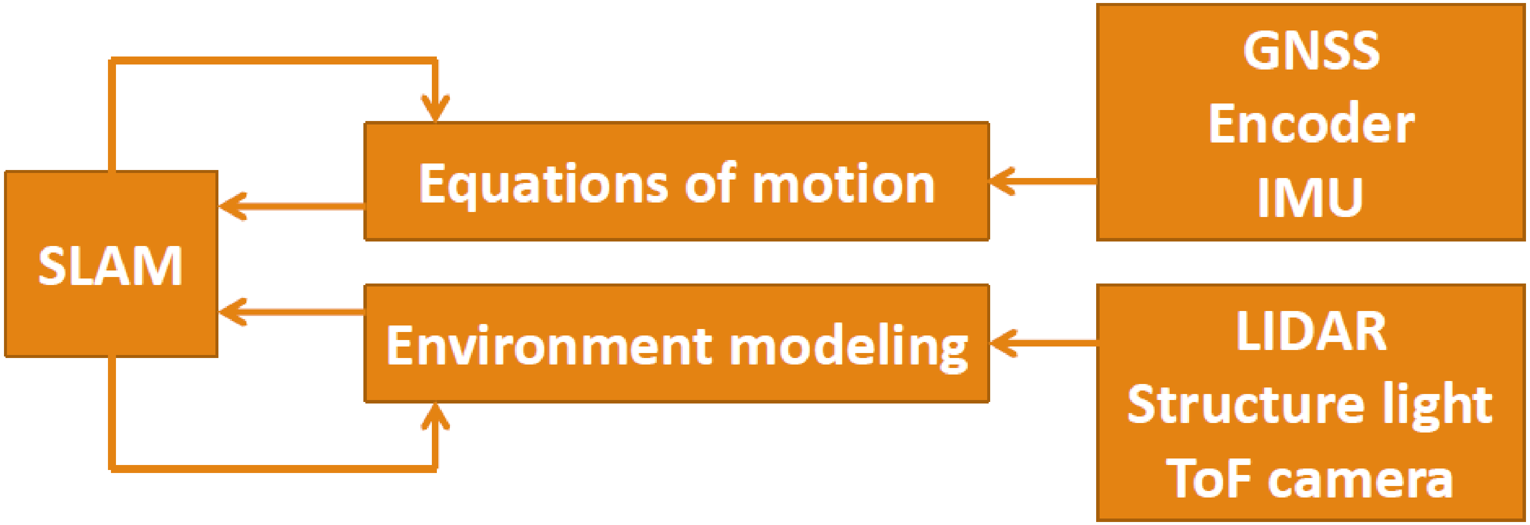
SLAM structure



Visual odometry

Attitude and position estimation is obtained by observing the change of the positions of static objects in two different frames.