上海科技大学
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CS283: **Robotics Spring 2024:   Sensors II**

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SENSORS

Introduction to Autonomous Mobile Robots page 102 ff

Classification of Sensors

- What:
  - Proprioceptive sensors
    - measure values internally to the system (robot),
    - e.g. motor speed, wheel load, heading of the robot, battery status
  - Exteroceptive sensors
    - information from the robots environment
    - distances to objects, intensity of the ambient light, unique features.
- How:
  - Passive sensors
    - Measure energy coming from the environment
  - Active sensors
    - emit their proper energy and measure the reaction
    - better performance, but some influence on environment

General Classification (1)

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

A, active; P, passive; P/A, passive/active; PC, proprioceptive; EC, exteroceptive.

General Classification (2)

General classification (typical use)	Sensor Sensor System	PC or EC	A or 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 geo-metric 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 analy-sis, segmentation, object recognition)	CCD/CMOS camera(s) Visual ranging packages Object tracking packages	EC	P

Characterizing Sensor Performance

- Basic sensor response ratings
  - Range
    - upper limit; lower limit

  - Resolution
    - minimum difference between two values
    - usually: lower limit of dynamic range = resolution
    - for digital sensors it is usually the A/D resolution.
      - e.g. 5V / 255 (8 bit)

  - Linearity
    - variation of output signal as function of the input signal
    - linearity is less important when signal is treated with a computer

$$x \to f(x)$$

$$y \to f(y)$$

$$\alpha \cdot x + \beta \cdot y \to f(\alpha \cdot x + \beta \cdot y) = \alpha \cdot f(x) + \beta \cdot f(y)$$

Characterizing Sensor Performance

- Bandwidth or Frequency
  - the speed with which a sensor can provide a stream of readings
  - usually there is an upper limit depending on the sensor and the sampling rate
  - lower limit is also possible, e.g. acceleration sensor
  - one has also to consider phase (delay) of the signal

- Sensitivity
  - ratio of output change to input change $\qquad \dfrac{dy}{dx}$

- Cross-sensitivity (and cross-talk)
  - sensitivity to other environmental parameters (e.g. temperature, magnetic field)
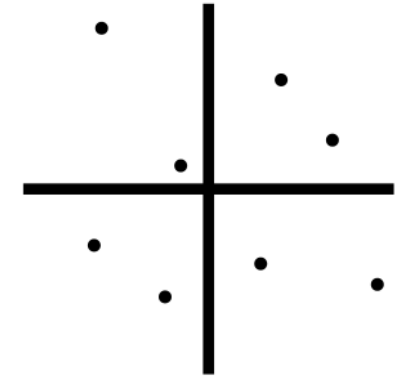 - influence of other active sensors

In Situ Sensor Performance

- In Situ: Latin for "in place"

- Error / Accuracy
  - How close to true value
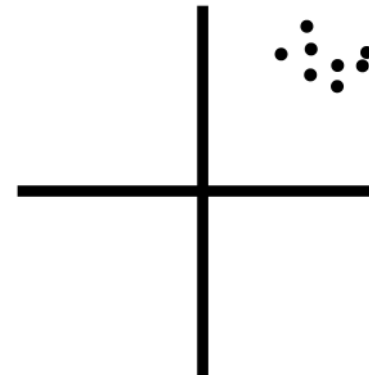- Precision
  - Reproducibility

$$\left(accuracy = 1 - \frac{|m - v|}{v} \right)$$

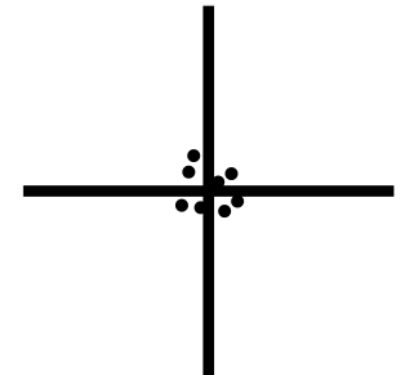*error*

m = measured value
v = true value
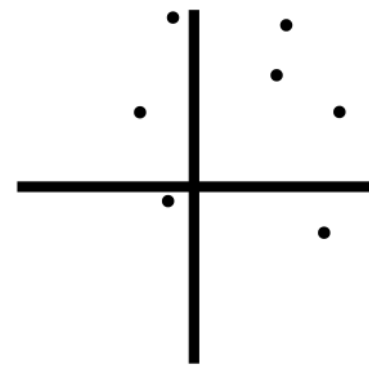
(a) Low precision and low accuracy

(b) Low precision and high accuracy

(c) High precision and low accuracy
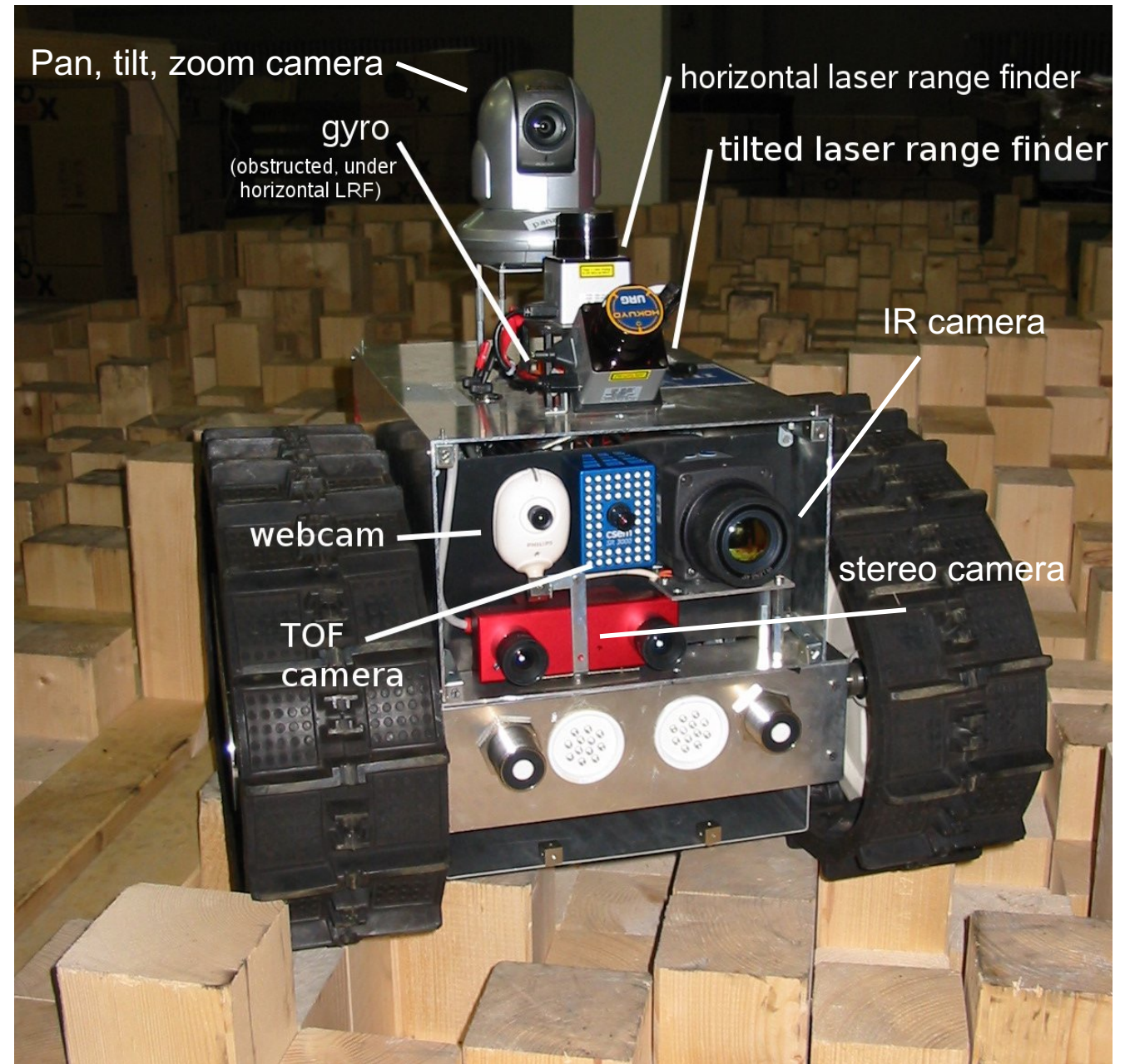
(d) High precision and high accuracy

Types of error

- Systematic error -> deterministic errors
  - caused by factors that can (in theory) be modeled -> prediction
  - e.g. calibration of a laser sensor or of the distortion caused by the optic of a camera

- Random error -> non-deterministic
  - no prediction possible
  - however, they can be described probabilistically
 - e.g. Hue instability of camera, black level noise of camera ..

Sensors: outline

- Optical encoders

- Heading sensors
  - Compass
  - Gyroscopes
  - Accelerometer
  - IMU

- GPS

- Range sensors
  - Sonar
  - Laser
  - Structured light

- Vision sensors:
  - separate lectures later

Pan, tilt, zoom camera
horizontal laser range finder
gyro (obstructed, under horizontal LRF)
tilted laser range finder
IR camera
webcam
stereo camera
TOF camera

Wheel / Motor Encoders

- measure position or speed of the wheels, motors or steering
- integrate wheel movements to get an estimate of the position -> odometry
- optical encoders are proprioceptive sensors
- typical resolutions: 64 - 2048 increments per revolution.
  - for high resolution: interpolation
- optical encoders
  - regular: counts the number of transitions but cannot tell the direction of motion
  - quadrature: uses two sensors in quadrature-phase shift. The ordering of which wave produces a rising edge first tells the direction of motion. Additionally, resolution is 4 times bigger
  - a single slot in the outer track generates a reference pulse per revolution
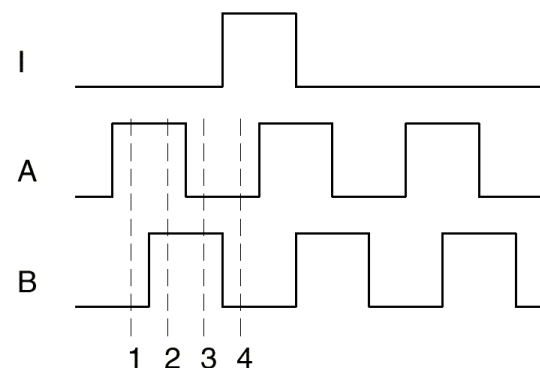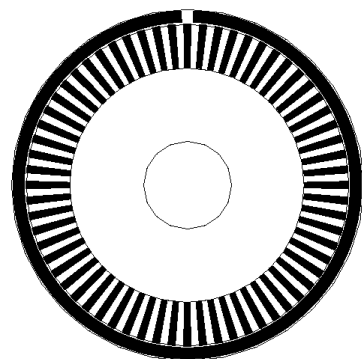
State	Ch A	Ch B
S_1	High	Low
S_2	High	High
S_3	Low	High
S_4	Low	Low

Gray Encoder

http://en.wikipedia.org/wiki/Gray_code
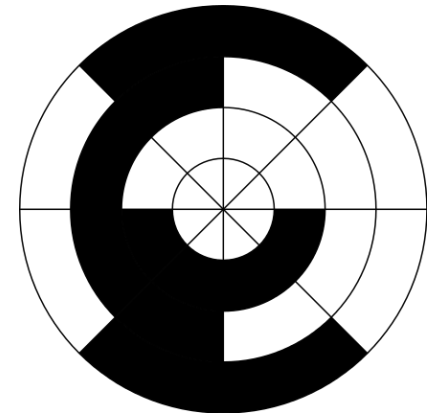
- Aka: reflected binary code, Gray Code
  - Binary numeral system where two successive values differ in only one bit
  - Also used for error correction in digital communications

- Absolute position encoder
  - Normal binary => change from 011 to 100
  - 2 bits change – NEVER simultaneously =>
  - 011 -> 111 -> 101 -> 100   or
  - 011 -> 010 -> 110 -> 100   ….
  - => wrong encoder positions might be read
  - Gray encoding: only one bit change!

| Dec	Gray	Binary
0	000	000
1	001	001
2	011	010
3	010	011
4	110	100
5	111	101
6	101	110
7	100	111

Heading Sensors

- Heading sensors can be proprioceptive (gyroscope, acceleration) or exteroceptive (compass, inclinometer).

- Used to determine the robots orientation and inclination.

- Allow, together with an appropriate velocity information, to integrate the movement to a position estimate.

  - This procedure is called **deduced reckoning** (ship navigation)

Compass

- Magnetic field on earth
  - absolute measure for orientation

- Large variety of solutions to measure the earth magnetic field
  - mechanical magnetic compass
  - direct measure of the magnetic field (Hall-effect, magneto-resistive sensors)

- Major drawback
  - 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 feasible for indoor environments for absolute orientation
 - useful indoor (only locally)
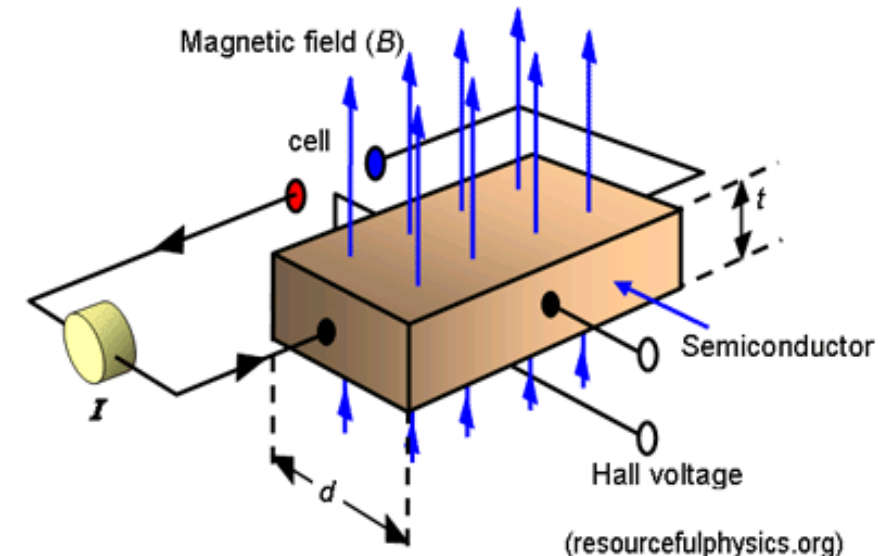
Gyroscope

- Heading sensors that preserve their orientation in relation to a fixed reference frame
  - absolute measure for the heading of a mobile system.

- Two categories, the mechanical and the optical gyroscopes
  - Mechanical Gyroscopes
    - Standard gyro (angle)
    - Rate gyro (speed)

  - Optical Gyroscopes
    - Rate gyro (speed)

Mechanical Gyroscopes

- Concept: inertial properties of a fast spinning rotor
- Angular momentum associated with a spinning wheel keeps the axis of the gyroscope inertially stable.
- No torque can be transmitted from the outer pivot to the wheel axis
  - spinning axis will therefore be space-stable
  - however friction in the axes bearings will introduce torque and so drift
- Quality: 0.1° in 6 hours (a high quality mech. gyro costs up to 100,000 $)

- If the spinning axis is aligned with the north-south meridian, the earth's rotation has no effect on the gyro's horizontal axis
- If it points east-west, the horizontal axis reads the earth rotation

Outer pivot

Wheel

C

Inner pivot

Wheel bearing

Inner gimbal
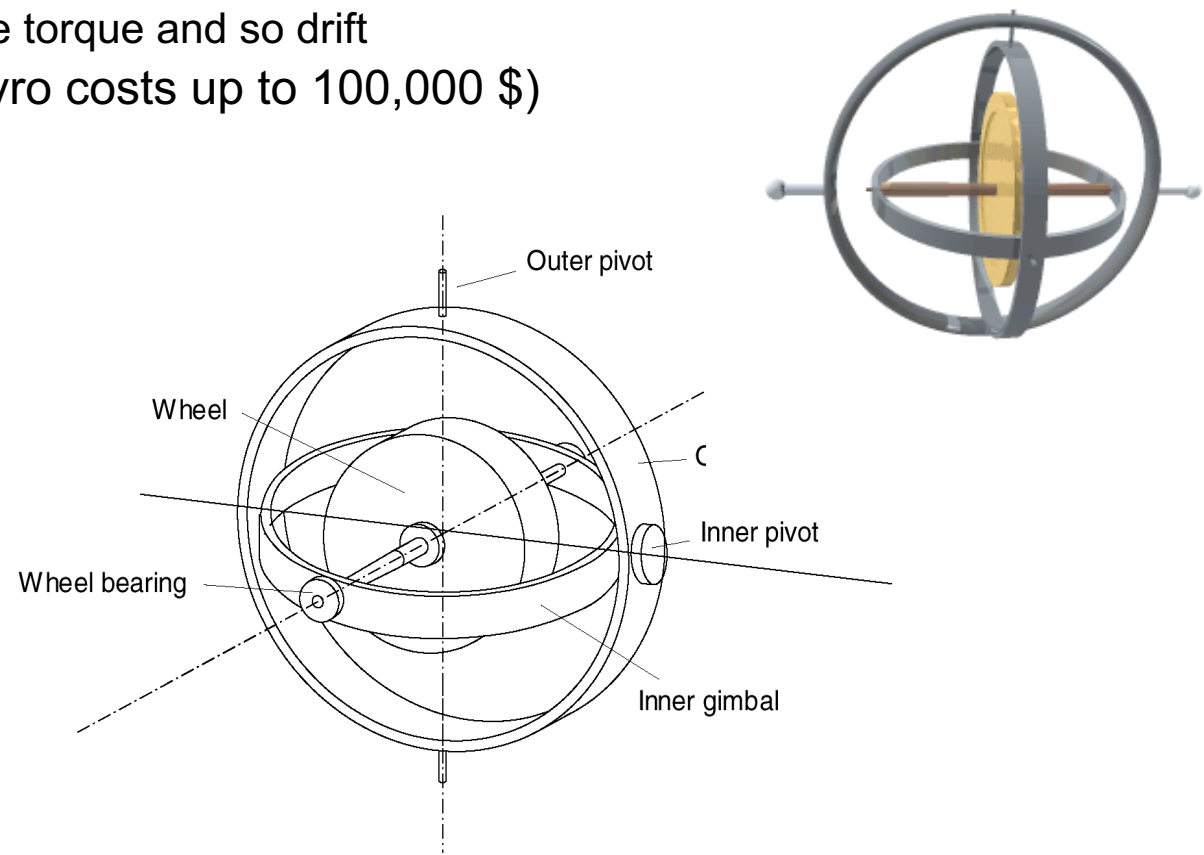
Optical Gyroscopes

- First commercial use: early 1980 in airplanes
- Optical gyroscopes
  - angular speed (heading) sensors using two monochromic light (or laser) beams from the same source.
- One is traveling in a fiber clockwise, the other counterclockwise around a cylinder
- Laser beam traveling in direction opposite to the rotation
  - slightly shorter path
  - phase shift of the two beams is proportional to the angular velocity Ω of the cylinder
  - In order to measure the phase shift, coil consists of as much as 5Km optical fiber
- New solid-state optical gyroscopes based on the same principle are build using micro-fabrication technology.

Single axis optical gyro

3-axis optical gyro

Light source

Detector

A
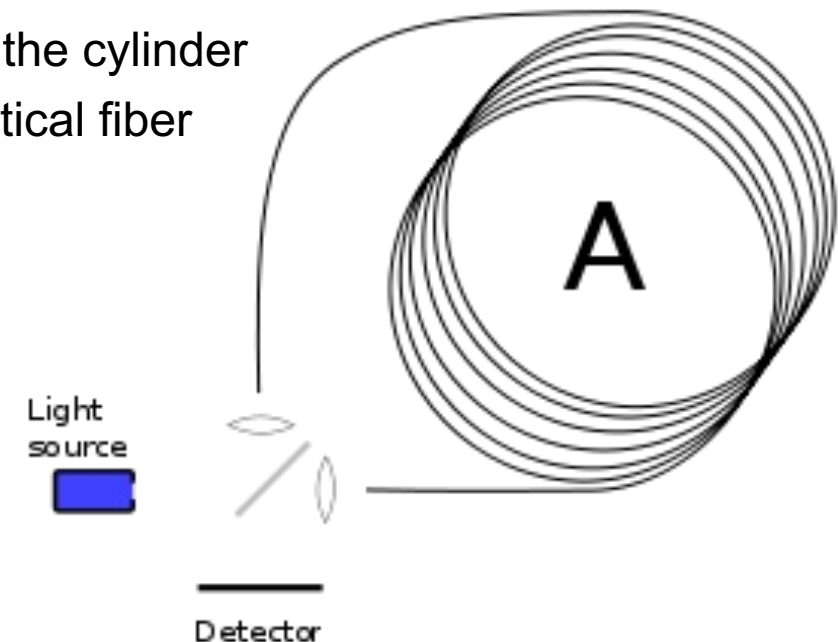
Mechanical Accelerometer

- Accelerometers measure all external forces acting upon them, including gravity
- Accelerometer acts like a spring–mass–damper system
- On the Earth's surface, the accelerometer always indicates 1g along the vertical axis
- To obtain the inertial acceleration (due to motion alone), the gravity must be subtracted.
- Bandwidth up to 50 KHz
- An accelerometer measures acceleration only along a single axis
- => mount 3 accelerometers orthogonally => three-axis accelerometer
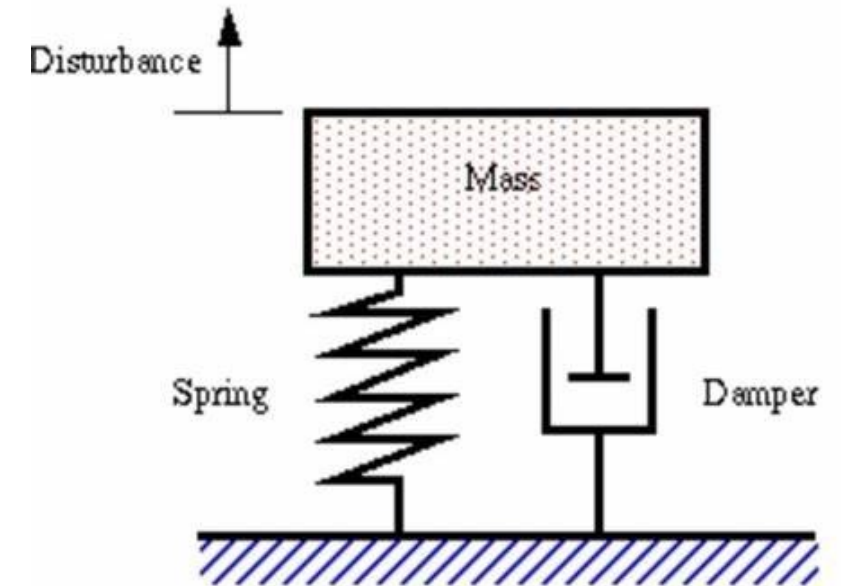
Factsheet: MEMS Accelerometer

seismic mass

motion

capacitive divider

<http://www.mems.sandia.gov/>
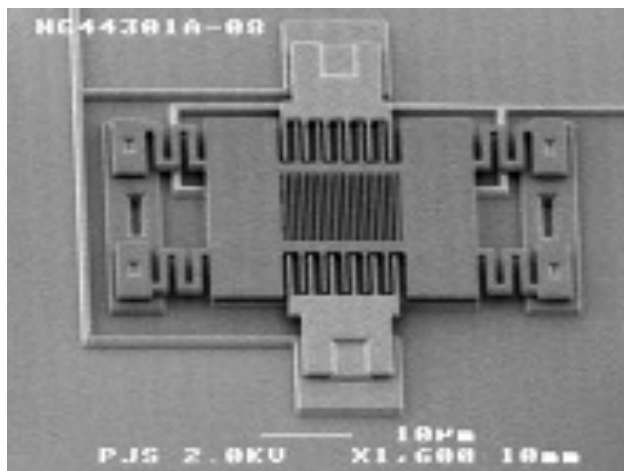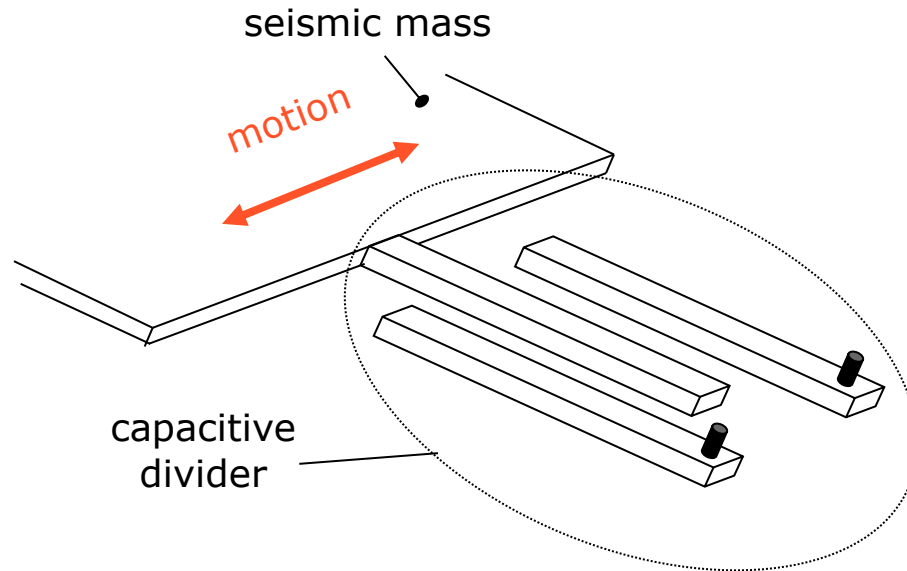
1. Operational Principle
The primary transducer is a vibrating mass that relates acceleration to displacement. The secondary transducer (a capacitive divider) converts the displacement of the seismic mass into an electric signal.

2. Main Characteristics
- Can be multi-directional
- Various sensing ranges from 1 to 50 g

3. Applications
- Dynamic acceleration
- Static acceleration (inclinometer)
- Airbag sensors (+- 35 g)
- Control of video games (Wii)

Inertial Measurement Unit (IMU)

- Device combining different measurement systems:
  - Gyroscopes, Accelerometers, Compass

- Estimate relative position (x, y, z), orientation (roll, pitch, yaw), velocity, and acceleration

- Gravity vector is subtracted to estimate motion
 - Initial velocity has to be known

Xsens MTI
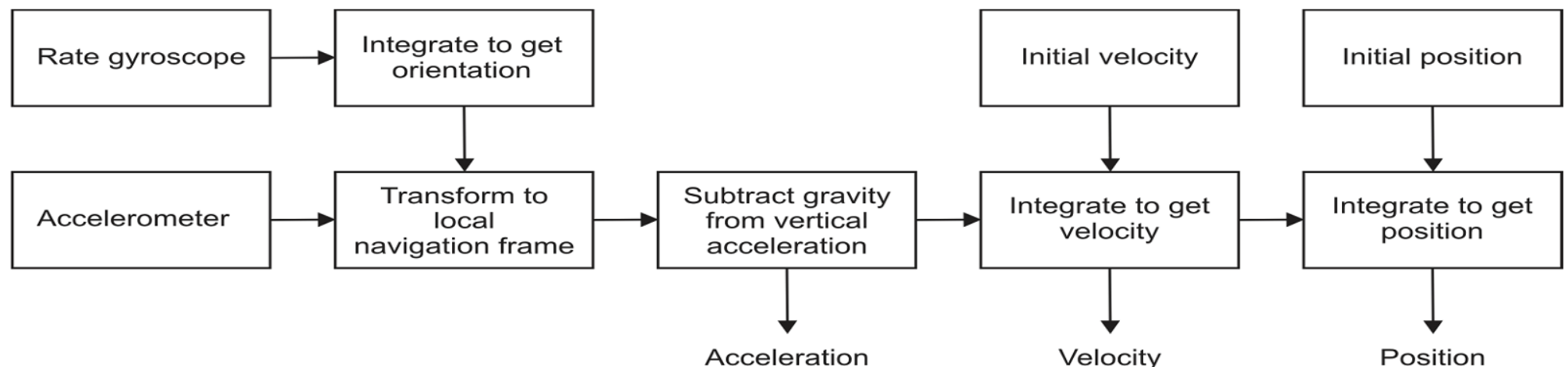
IMU Error and Drift

- Extremely sensitive to measurement errors in gyroscopes and accelerometers:
  - drift in the gyroscope unavoidably =>
  - error in orientation relative to gravity =>
  - incorrect cancellation of the gravity vector.

- Accelerometer data is integrated twice to obtain the position => gravity vector error leads to quadratic error in position.

- All IMUs drift after some time
  - Use of external reference for correction:
  - compass, GPS, cameras, localization

Global Positioning System (GPS)

- Developed for military use
- 1995 it became accessible for commercial applications
- 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. The orbital planes do not rotate with respect to stars. Orbits arranged so that at least 6 satellites are always within line of sight from any point on Earth's surface.
- From 2008: 32 satellites to improve localization accuracy through redundancy
- 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
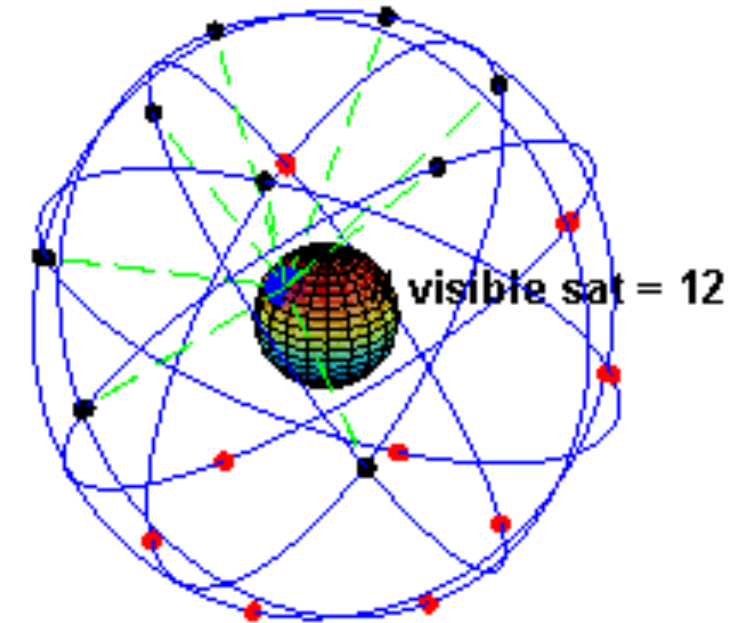
Global Positioning System (GPS) (2)
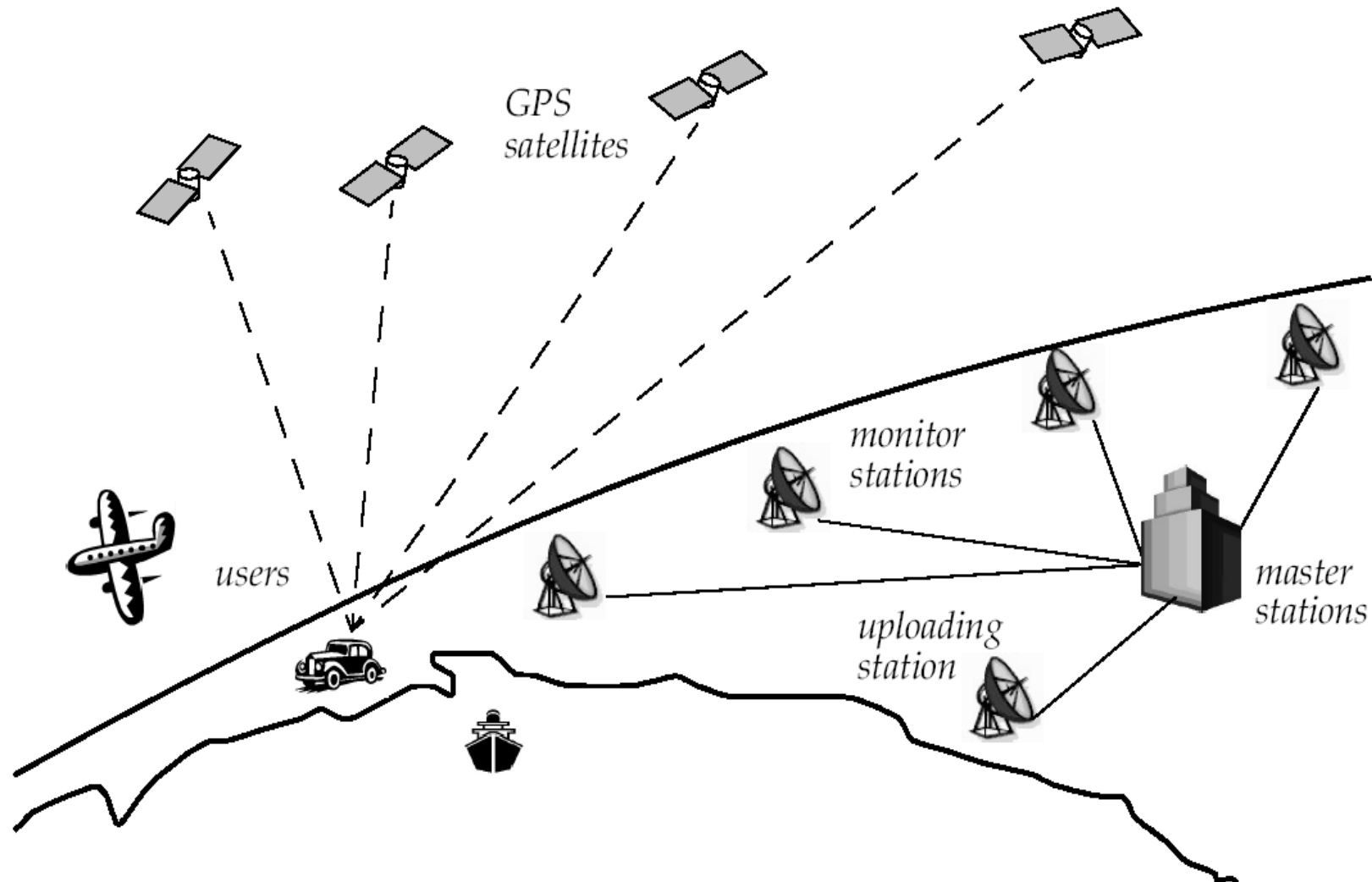
Global Positioning System (GPS) (3)

- 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
- 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
- Recent commercial GPS receiver devices allows position accuracies down to a couple meters.

GPS Error Sources

Satellite clock errors uncorrected by monitor stations may result in one meter errors:

- Ephemeris data errors: 1 meter

- Tropospheric delays: 1 meter.
  - The troposphere is the lower part (ground level to from 8 to 13 km) of the atmosphere that experiences the changes in temperature, pressure, and humidity associated with weather changes. Complex models of tropospheric delay require estimates or measurements of these parameters.

- Unmodeled ionosphere delays: 10 meters.
  - The ionosphere is the layer of the atmosphere from 50 to 500 km that consists of ionized air. The transmitted model can only remove about half of the possible 70 ns of delay leaving a ten meter un-modeled residual.

- Number of satellites under line of sight

GPS Multipath

- Multipath: 0.5 meters

  - Multipath is caused by reflected signals from surfaces near the receiver that can either interfere with or be mistaken for the signal that follows the straight line path from the satellite. Multipath is difficult to detect and sometime hard to avoid.

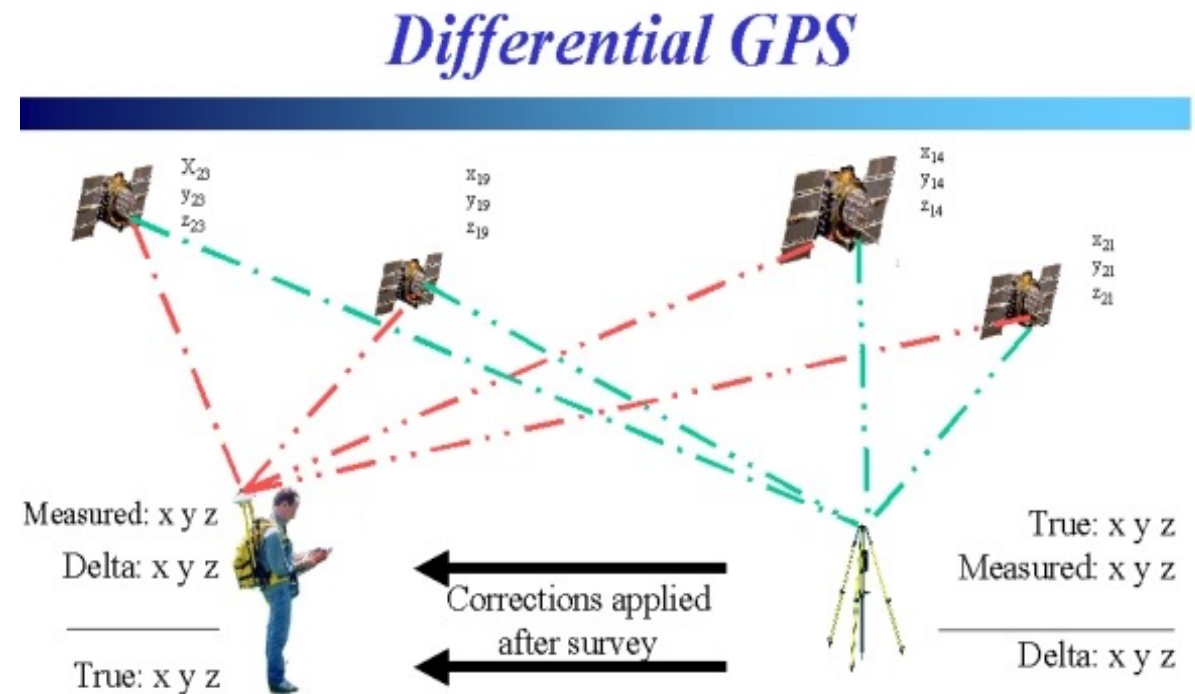Satellite coverage
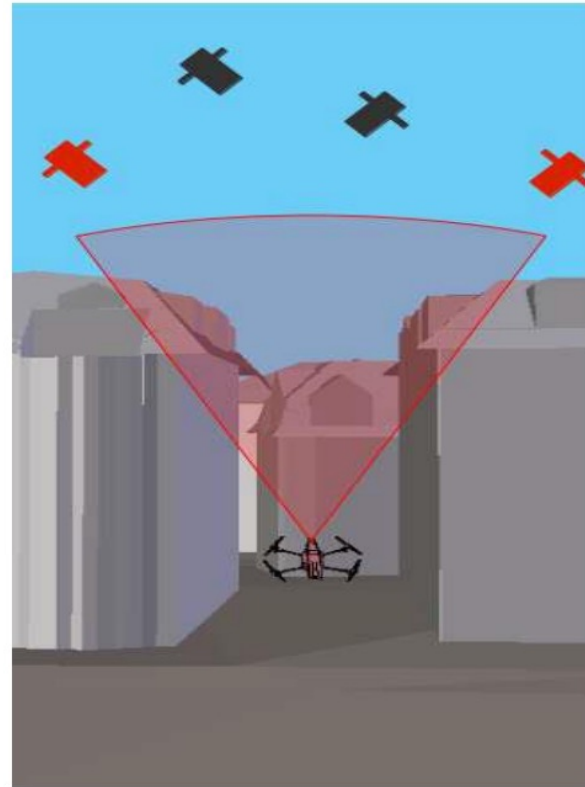
Multipath problem
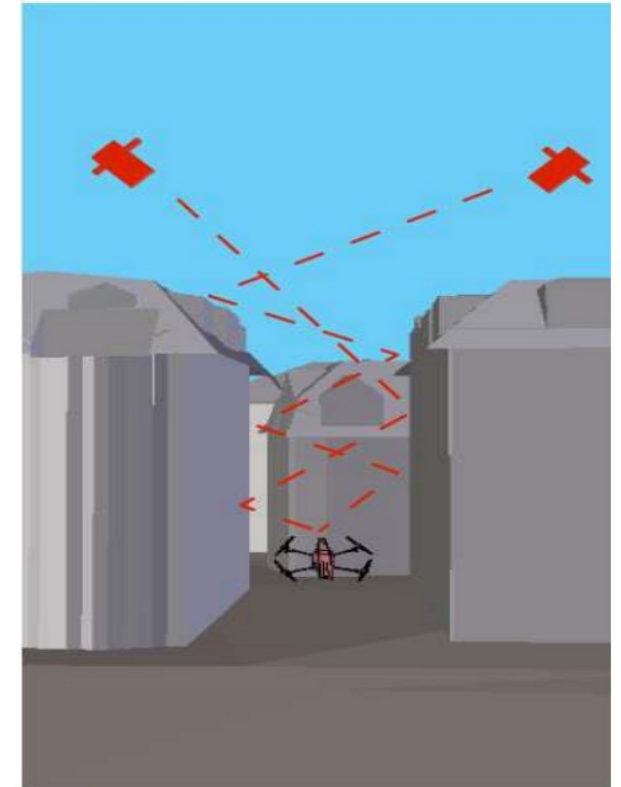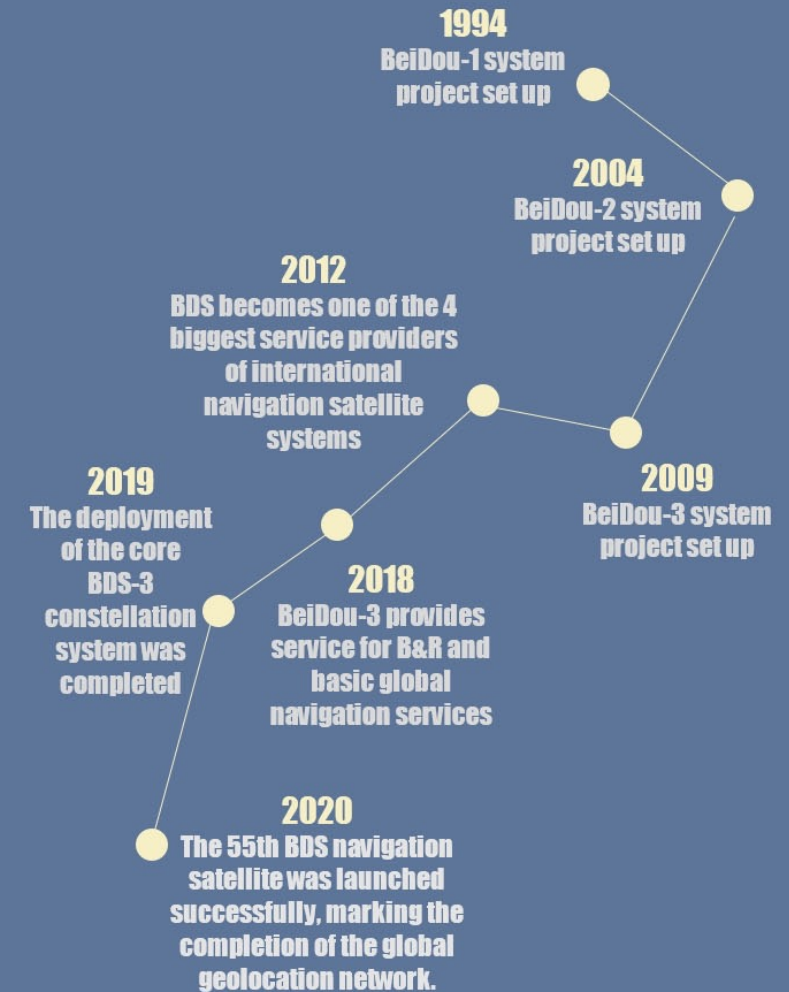
Differential Global Positioning System (dGPS)

- Base station GPS receiver: set up on a precisely known location

- Base station receiver calculates its position based on satellite signals

- Compares this location to the known location

- Difference is applied to the GPS data recorded by the mobile GPS receivers

- Position accuracies in sub-meter to cm range

Other Global Positioning Systems

- GLONASS
  - Russian GPS – developed since 1976
  - Full global coverage as of 2011 (24 sattelites)
- Galileo
  - European GPS – initiated 2003
  - 22 operational satellites in orbit
- IRNSS (Indian Regional Navigation Satellite System)
  - Initiated 2010
  - 8 satellites for Indian Coverage in orbit
  - Full operation
- BeiDou Navigation Satellite System 北斗卫星导航系统
  - Chinese GPS – developed since 1994
  - BeiDou Satellite Navigation System (BDS)
  - 2011 full China coverage – 2019 global coverage
  - 55 satellites system

Key Moments of BDS' Development

1994
BeiDou-1 system project set up

2004
BeiDou-2 system project set up

2012
BDS becomes one of the 4 biggest service providers of international navigation satellite systems

2019
The deployment of the core BDS-3 constellation system was completed

2009
BeiDou-3 system project set up

2018
BeiDou-3 provides service for B&R and basic global navigation services

2020
The 55th BDS navigation satellite was launched successfully, marking the completion of the global geolocation network.

A more ubiquitous, mixable, intelligent national navigation system based on BDS is planned to be finished by **2035**.

GPS coordinate errors

- HD maps: save locations in coordinates
  (e.g. location of traffic light)
- Many sources of errors – e.g.:
  - Wrong survey (input data is wrong)
    - Human error and instrument error
  - Continental drift! (Australia: 7 cm per year!)

- China: GCJ-02: WGS 84 plus random offsets
  (about 300-500m) (for national safety)
  makes autonomous driving development difficult :/
  地形图非线性保密处理算法
  - Called "Mars coordinate system"
  - Need special license to calculate correct position
  - afaik: 7 companies in China have this license

- Baidu: BD-09 further offsets (so competitors don't copy)

Australia Is Drifting So Fast GPS Can't Keep Up

A significant correction must be made by the end of the year for navigation technology to keep working smoothly.

BY **BRIAN CLARK HOWARD**

NATIONAL GEOGRAPHIC

PUBLISHED SEPTEMBER 24, 2016 • 2 MIN READ

Australia is not quite where you think it is. The continent has shifted by 4.9 feet since the last adjustment was made to GPS coordinates in 1994, reports the *New York Times*.

All of the Earth's continents float on tectonic plates, which glide slowly over a plastic-like layer of the upper mantle. And the plate that Australia sits on has been moving relatively fast, about 2.7 inches a year (northward and with a slight clockwise rotation).

https://www.nationalgeographic.com/science/article/australia-moves-gps-coordinates-adjusted-continental-drift