Positioning Techniques

Lecture 9

Goal of this lecture

- Methods of positioning in 2D, 3D space.
- Standard techniques for mobile systems and applications.
- Usage of the positioning solutions on mobile systems.

Content

- About positioning
- GPS – global positioning
- LPS – local positioning
  - WPS (WLAN positioning)
  - WSN (sensor networks)
- Other hybrid solutions

About positioning

Location of a mobile device can be used by applications as an automatic input.

Positioning can be used:

- By location-aware services (recommender systems)
- Part of the user/device context for context-aware services
- Navigation
- Neighbor equipment for ad-hoc communication

Application types

Location-aware, location-based

- Provide services based on user’s location

Time-aware

- Provide services specific to the time of usage: time-of-day, day-of-week

Context-aware

- Provide services based on multiple user’s parameters: location, time, type of movement, temperature, etc.

User-aware

- Provide and personalize services specific to the user that consume them (user patterns, behavior, emotions)

Positioning context

Any information that can be used to characterize the status of an entity.

An entity can be a person, place, or object.

Low-level contexts:

- location, time, nearby objects,
- networking configurations, orientation,
- environment: light, temperature, pressure, sound, pollution, etc.

Positioning context

High-level contexts:

- user context (location, task)
- social context (e.g., *social status* of the user or of the location)
- personal context (e.g., user's emotions, user's intention and preferences).

Positioning systems (PS)

Global:

- GPS – global positioning system
- Galileo
- Glonass

Are all outdoor PS

Moderate-high accuracy, between 1-15m

Positioning systems (PS)

Local:

- LPS – local positioning system
- IPS – indoor positioning system
- WPS – wireless positioning system

Are all indoor PS

High accuracy, below 1m

Positioning techniques

- Lateration (trilateration)
- Hyperbolic lateration (multilateration)
- Angulation (triangulation)
- Proximity detection
- Inertial navigation
- Fingerprinting
- SLAM

Source: [Springer]

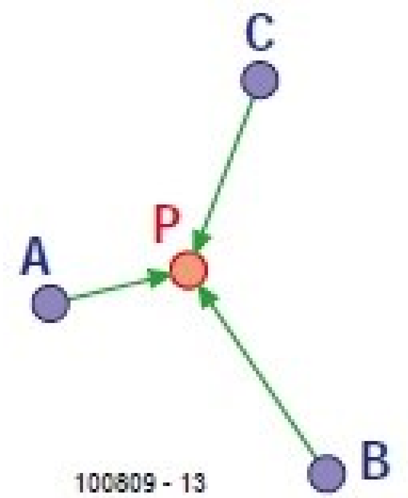
Trilateration

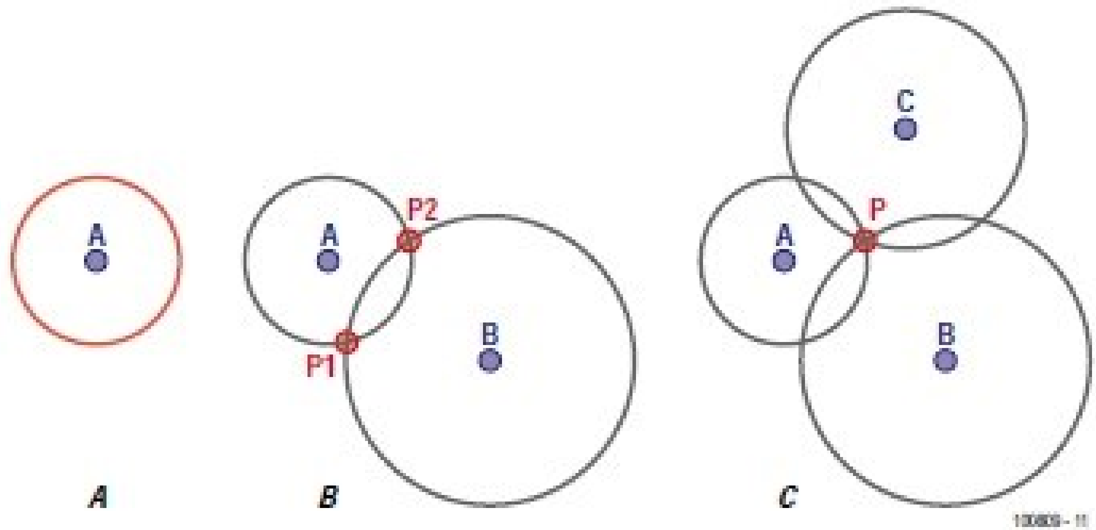
A) Knowing the distance to a fixed station, the mobile station could be anywhere along the circle with center A and distance as the radius

B) Knowing the distance to two fixed stations, the mobile station could be at the intersection of both circles

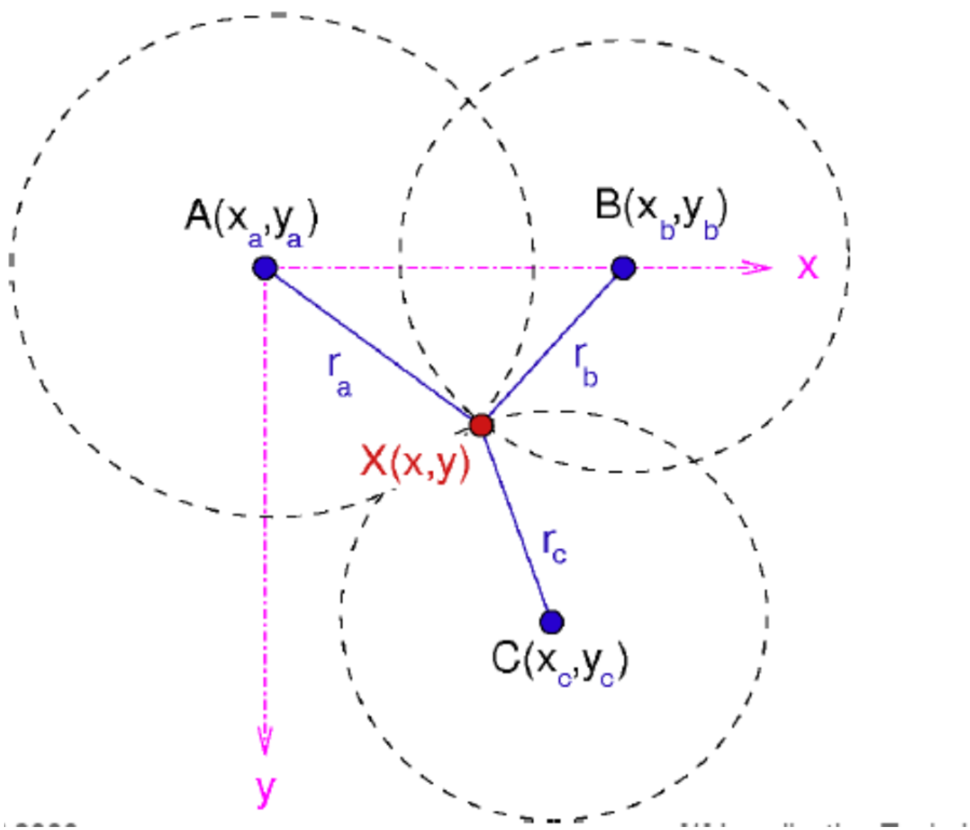
C) Knowing the distance to three fixed stations, the mobile station could be at the intersection of all three circles

Trilateration





Trilateration – maths enthusiasts



$$\begin{cases} x^2 + y^2 & = r_a^2 \\ (x - x_b)^2 + y^2 & = r_b^2 \\ (x - x_c)^2 + (y - y_c)^2 & = r_c^2 \end{cases}$$

$$x = \frac{x_b^2 + r_a^2 - r_b^2}{2x_b}$$

$$y = \frac{x_c^2 + y_c^2 + r_a^2 - r_c^2 - 2xx_c}{2y_c}$$

Trilateration

Requires the distance between the receiver and transmitter to be measured.

- Received Signal Strength Indicator (RSSI), or
- Time of arrival (ToA)—or time of flight (ToF)

The receiver and transmitter must be synchronized — for example, by means of a common timebase, as in GPS

Trilateration

Three non-collinear reference points for 2D positioning

Four non-collinear reference points for 3D positioning

This explains why a GPS needs to see at least four satellites to work.

Multilateration

Using a single receiver listening to the signals (pulses) from two synchronized transmitters, it is possible to measure the difference between the arrival times (time difference of arrival, or **TDoA**) of the two signals at the receiver.

Then the principle is similar to trilateration, except that we no longer find ourselves on a circle or a sphere, but on a hyperbola (2D) or a hyperboloid (3D). Here too, we need four transmitters to enable the receiver to calculate its position accurately.

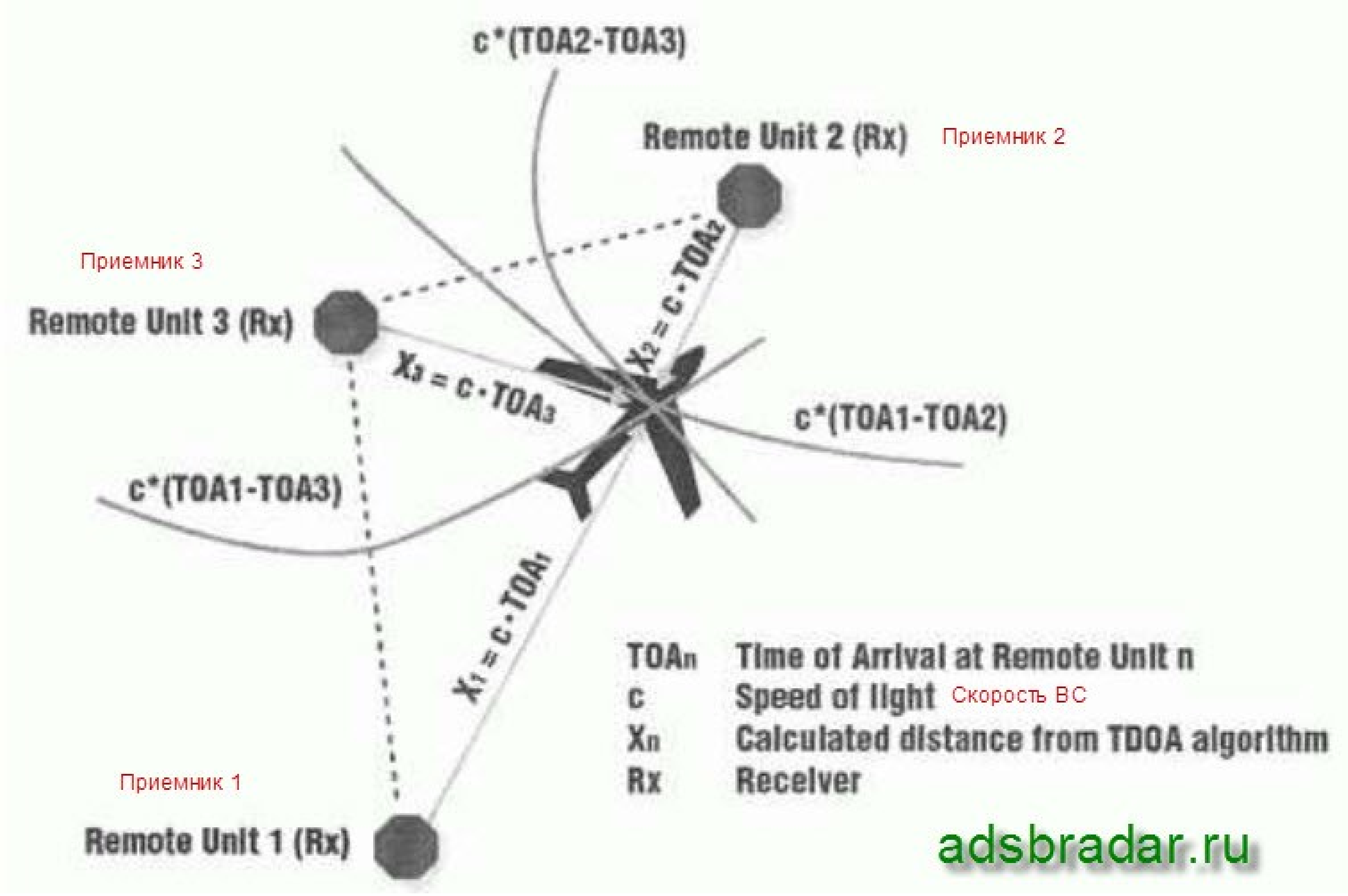
Multilateration

Advantage:

The receiver doesn't need to know at what instant the signals were transmitted, i.e. hence the receiver doesn't need to be synchronized with the transmitters.

The signals & electronics can be kept simple

Multilateration example



Triangulation

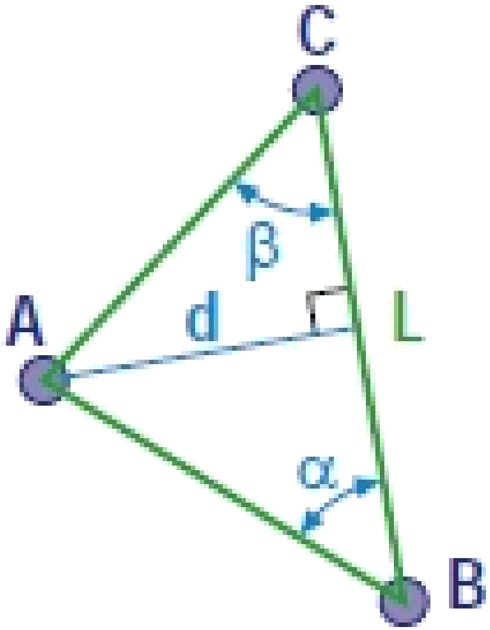
Over 2,500 years old method, used by Thales of Miletus to measure the radius of the Earth's orbit around the Sun.

Allows an observer to calculate their position by measuring two directions towards two reference points. Since the positions of the reference points are known, it is possible to construct a triangle where one of the sides and two of the angles are known, with the observer at the third point.

Triangulation

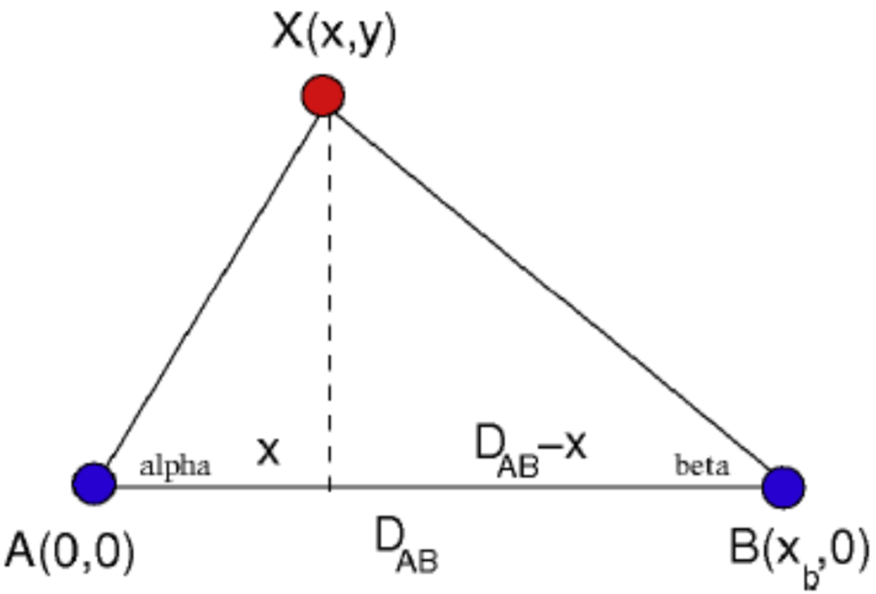
You are at A, from where you can see B and C.

If you know their geographical positions, you can find your own position with the help of a compass.



$$d = \frac{L \sin(\alpha) \sin(\beta)}{\sin(\alpha+\beta)}$$

Triangulation – maths enthusiasts



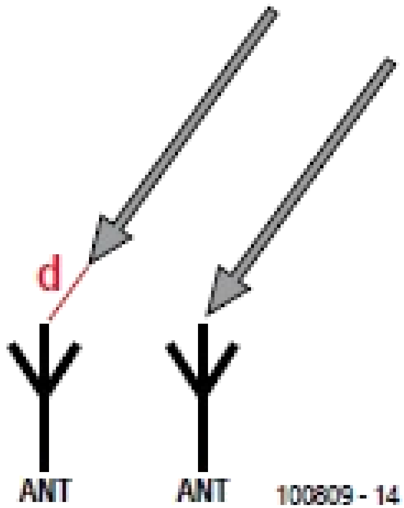
$$x = \frac{\tan\beta}{\tan\alpha + \tan\beta}$$

$$y = \frac{\tan\beta \cdot \tan\alpha}{\tan\alpha + \tan\beta}$$

Triangulation

Using transmitters requires the angle of incidence (angle of arrival, or AoA) of a radio signal to be measured.

→ Use several antennas placed side by side (an array of antennas) and measure the phase difference between the signals received by the antennas.



Proximity detection

Based on the proximity of the mobile device to previously known locations.

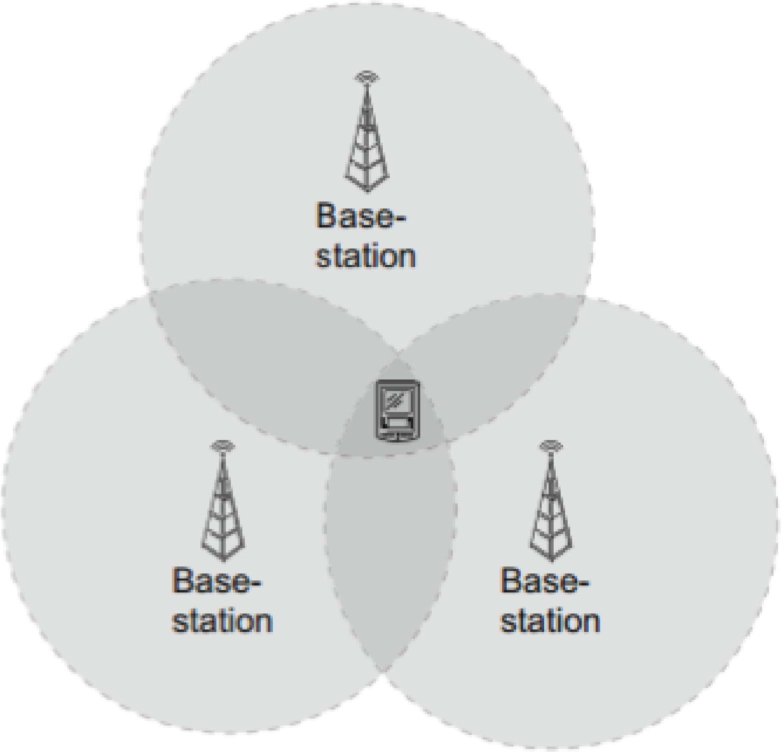
E.g. the visibility of a Wi-Fi network results in proximity to the access point as the Wi-Fi signal is limited to a region around the access point.

→Sets of possible locations (WiFi ~ circle)

→Proximity to several different locations can be used to intersect these sets

→Intersection of circles

Proximity detection



Inertial navigation

Uses only measurements made inside the inertial system of the mobile device.

- Location, speed, and orientation at the starting time are known
- Measurements are used to update this complete movement state
- Inertial navigation is usually based on measuring acceleration and rotation
- Sometimes, odometrical measurements including steps, as well as steering angles can also be used

Inertial navigation

IMU (Inertial measurement unit): six elementary sensors measuring acceleration in three pairwise orthogonal directions and three gyroscopes each measuring rotation around one axis.

Advantage: device is autonomous.

Drawback: location of a device cannot be observed directly from within the inertial frame of the mobile device. Measurement errors in sensor data will accumulate over time rendering inertial navigation systems useless after a specific amount of time.

Fingerprinting

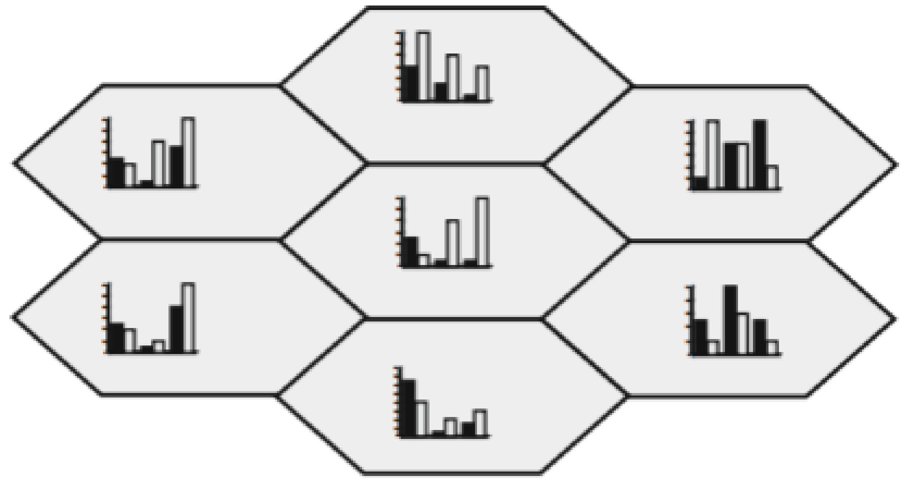
Previous approaches: all based on observing a known physical relation between some measurable size and location.

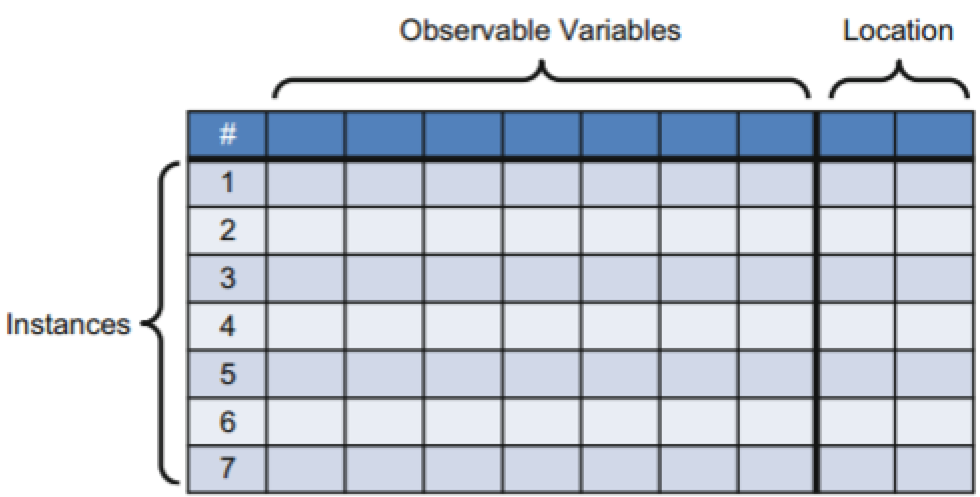
Different approaches: reproducibility of patterns of measurable variables.

The set of measurements at a specific location is similar to the set of measurements taken at the same location at another time or with another device, but **not** similar to measurements taken at **another place**.

Fingerprinting

Data mining algorithms





Source: Werner, M., 2014. Basic Positioning Techniques. In *Indoor Location-Based Services* (pp. 73-99). Springer International Publishing.

Fingerprinting

Based on available information:

- Supervised Learning: for each instance of the training dataset, the location is given.
- Unsupervised Learning: instead of searching for a model predicting location out of observable variables, unsupervised learning tries to find relations between attributes of instances.
- Semi-supervised Learning: Both approaches are combined into a prediction model built from the training data containing location, and unsupervised learning is being used to enhance this model further.

SLAM - simultaneous localization and mapping

Light-based solution for indoor positioning motivated from the fact that most building material can reflect light.

- LiDAR system (light detection and ranging)
- Used to generate maps of the surroundings using techniques of simultaneous localization and mapping (SLAM)
- Microsoft Kinect sends out a pattern of light recollected using a camera

Examples of PS

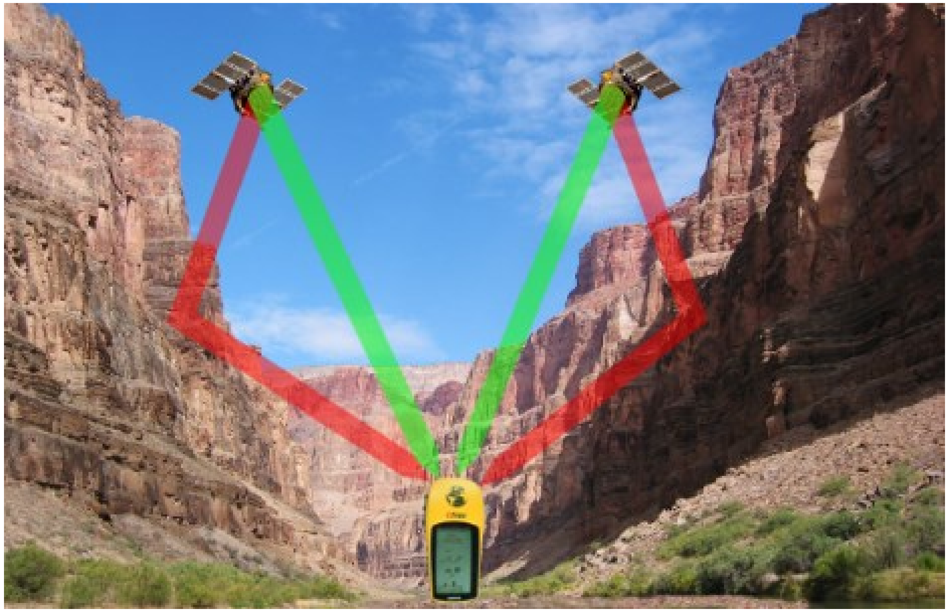
- High sensitivity GNSS (global navigation satellite systems)
  - Path loss and multipath effects inside buildings
- Light-based systems (LiDAR, Active Badge)
- Camera-based systems – using visual sense
  - Mobile camera, or fixed camera which follows target movement
- Radio-based systems – highly accurate inside buildings
  - RADAR, WiFi, RFID
- Inertial navigation – using IMUs
- Audio-based systems – using WSN and ultrasounds
- Pressure-based systems – e.g. sensors in the floor

Summary of positioning techniques

Algorithm	Input sizes	Limitations
Lateration	Length, distance, time	Time synchronization, multipath
Hyperbolic lateration	Length differences, delays	Only infrastructure needs to be time synchronized
Angulation	Angles, phase differences	Multipath
Proximity detection	Visibility, physical proximity	Simple and reliable, often only coarse location
Inertial navigation	Acceleration, rotation, movement	Errors accumulate Independent from infrastructure
Fingerprinting	Feature vectors	Stable with respect to multipath and complexities, sensitive to (small) changes in the environment
SLAM	Inertial navigation, depth images	Often accurate, independent from infrastructure, computationally challenging

Multipath effect

Radio signals reaching the receiving antenna by two or more paths. Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from water bodies and terrestrial objects such as mountains and buildings.



Methods for measuring distances

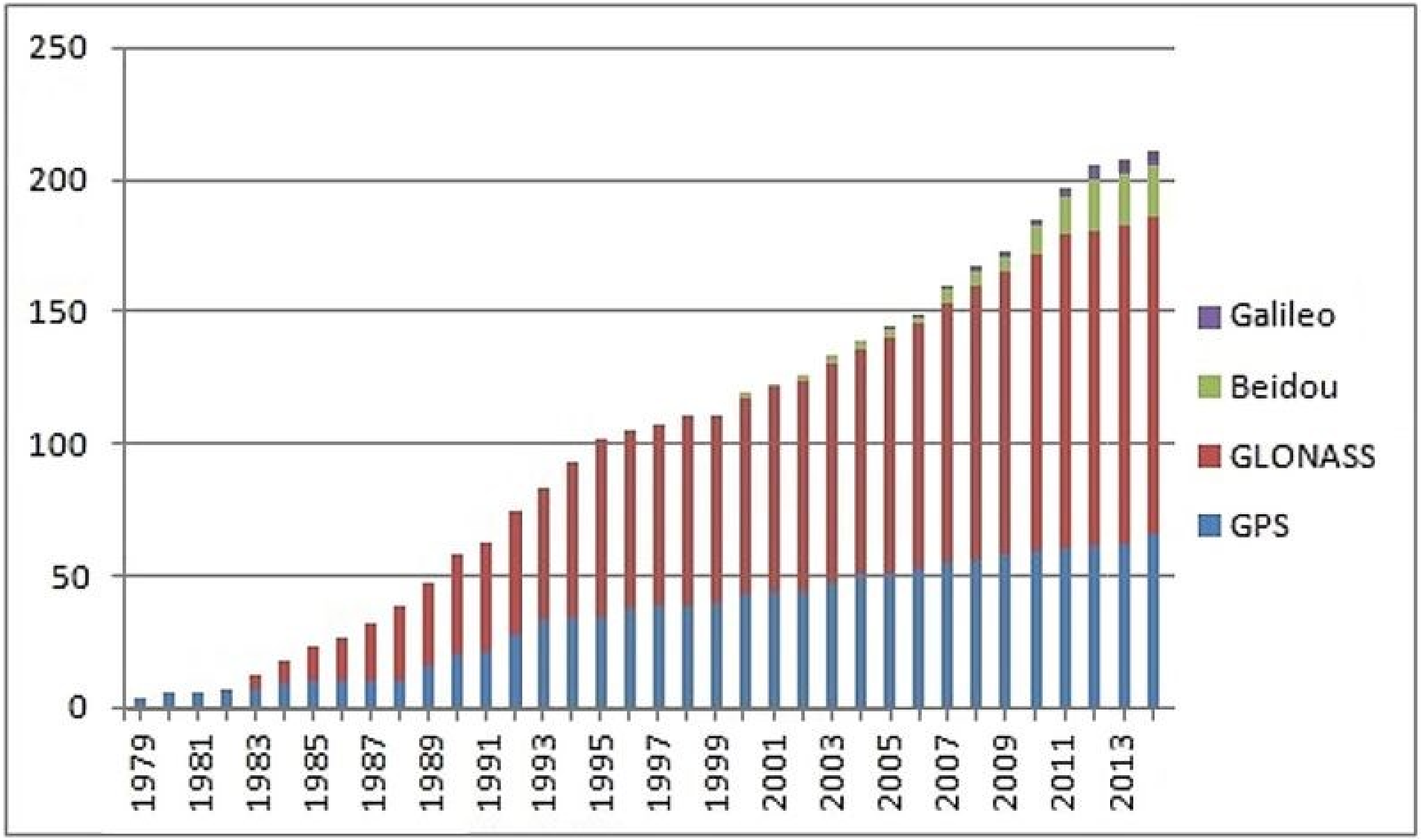
- RSSI - Received Signal Strength Indicator
  - Measures the received signal strength at the receiver.
  - Estimates the distance between transmitter and receiver, knowing the transmission power.
- ToA – Time-of-Arrival
  - Measures the signal propagation time to estimate the distance between transmitter and receiver.
  - Requires accurate clock synchronization between transmitter and receiver.
- TDoA – Time-Difference-of-Arrival
  - Measures the signal propagation delay between two transmission stations with known positions.
- AoA – Angle-of-Arrival
  - Measures the arrival angle of the signal at the receiver.
  - Requires special antenna to detect the angle.

Global Navigation Satellite Systems

- USA – NAVSTAR **GPS** (1993)
- Russia – **GLONASS** (1993-2009), (2010-2011 – global coverage)
- EU – **Galileo** (2011 – first two satellites, 2019 - deadline)
- China – BeiDou-1 (2000, China), -2 (2012, Pacific), -3 (2020, global)
- Japan – QZAA (Quasi-Zenith Satellite System, 2010)
- India – NAVIC (NAVigation with Indian Constellation, 2016)
- *France – DORIS (static land-based system)*

More info [online]

Launched GNSS satellites 1978-2014



GPS

GPS – is a Global Navigation Satellite System for determining the positions of receivers using signals broadcast by satellites.

GPS consists of 3 main elements (called segments):

- Spatial segment
- Control segment
- User segment

GPS – Spatial segment

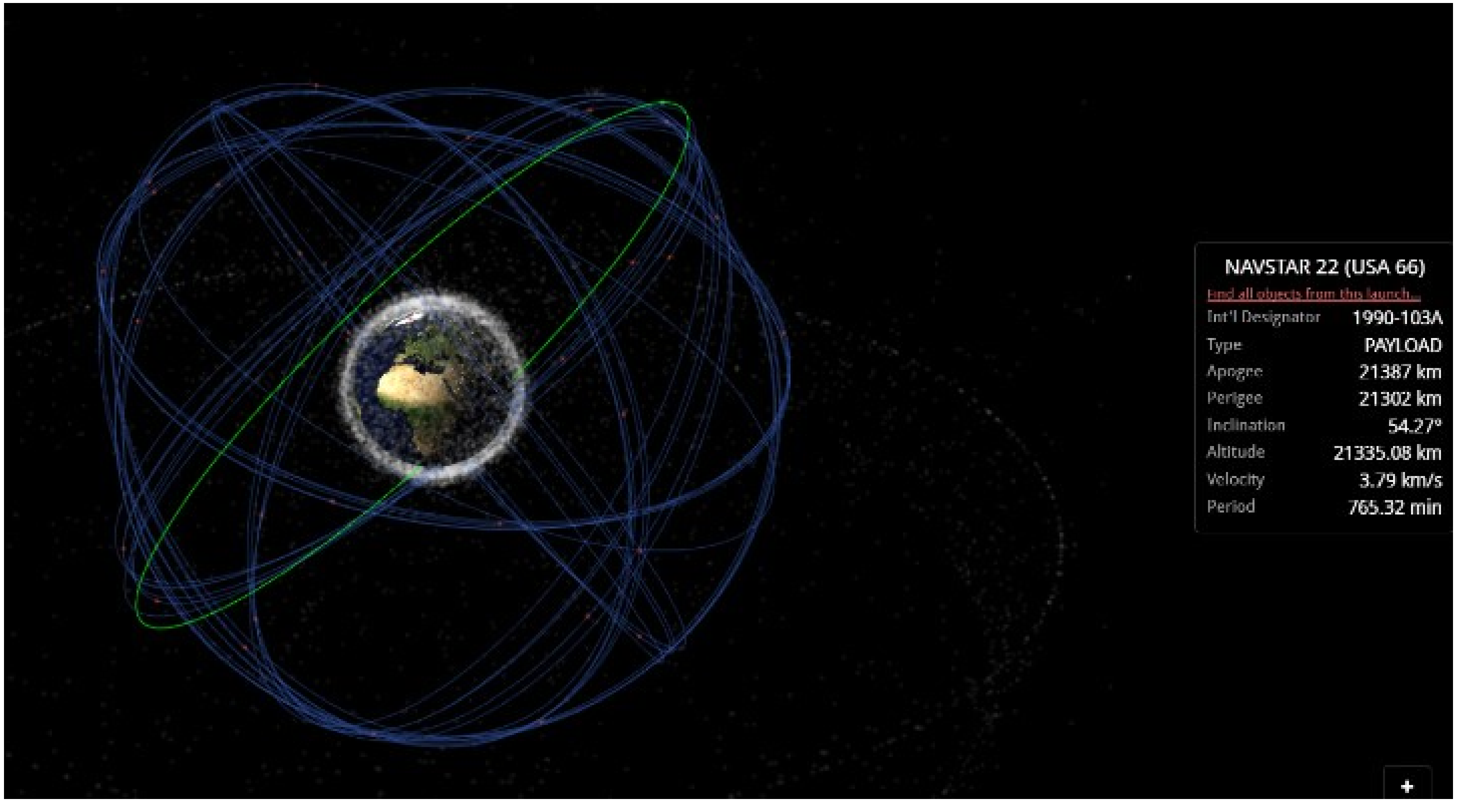
24 original satellites, upgraded to 32 (total: $5BN)

First launch: Feb 1978, 72 launches, operational by 1993

- Satellites have fixed orbits
- The satellites complete the orbit in 12hours
- There are 4 satellites in each of the 6 orbital planes
- 20,180 km altitude
- Each plane has an inclination of 55 degrees, separated by 60 degrees right ascension
- 5-8 satellites are visible in any place on Earth

GPS – Spatial segment

View spatial segment: http://stuffin.space/



GPS – Control segment

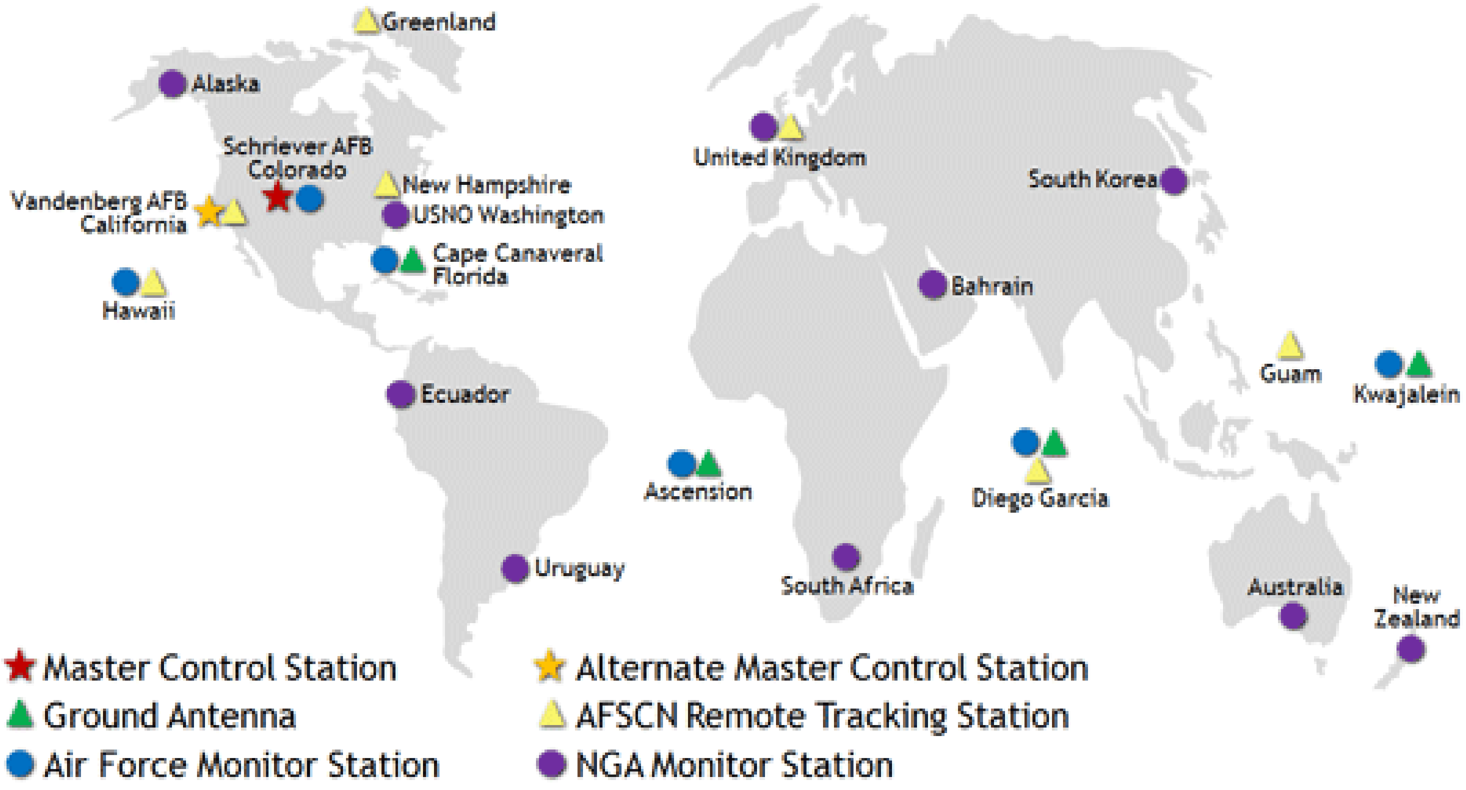
The satellites are monitored and controlled from 5 fixed stations on Earth (close to the Equator)

The control stations:

- Monitor and measure the signals transmitted by the satellites
- Compute the positioning data (ephemeris) and the corrections needed to be sent to the satellites
- Send the corrections back to the satellites

GPS – Control segment

1 master (MCS), 1 alternate master, 4 dedicated antennas, 6 monitor stations



GPS – User segment

- Civil – Standard Positioning Service (tens of millions)
- Military – Precise Positioning Service (hundreds of thousands)

GPS receivers compute and provide the position

GPS – User segment

Civilian applications

- Agriculture, astronomy, automated vehicles, cellular technology, clock synch, disaster relief, aircraft, fleet, navigation, robotics, sports, tectonics etc.

Military applications

- Navigation, target tracking, missile guidance, reconnaissance, nuclear detonation detection etc.

GPS characteristics

- All satellites have 4 atomic clocks synchronized to each other
- All satellites know their position from the data sent by the control stations
- Satellites continuously broadcast the position and the time using radio signals
- The radio signal is received at the destination with a delay proportional to the distance from the satellites
- The receiver computes the distance to the satellites using the received signal delay and estimates its position

GPS position estimation

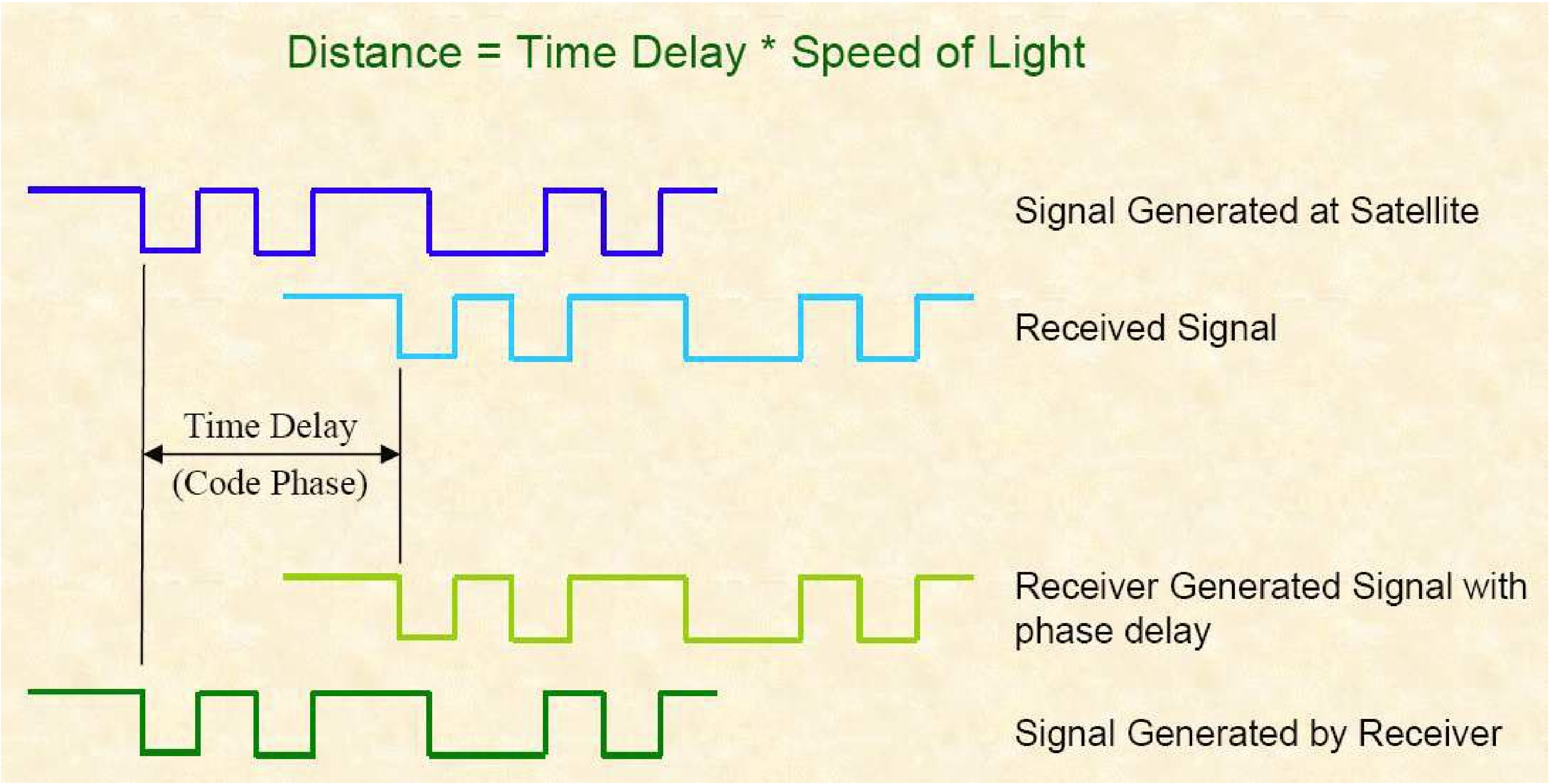
1. Receiver measures approximate distance to several satellites
2. Obtain the satellite position
3. Trilateration: Calculate the receiver's position using the distance measurements to satellites and knowledge of satellite locations
4. Correct for clock errors to improve position accuracy

GPS distance measurement

Is achieved using the signal propagation delay from the satellite to the receiver (ToA)

- The receiver generates locally the same signal broadcasted by the satellites in order to compute the delay.
- The receiver compares the generated signal with the received one to estimate the delay.

GPS distance measurement



GPS distance measurement

1. Distance to a satellite is determined by measuring how long a radio signal takes to reach us from that satellite.
2. To make the measurement we assume that both the satellite and our receiver are generating the same pseudo-random codes at exactly the same time.
3. By comparing how late the satellite's pseudo-random code appears compared to our receiver's code, we determine how long it took to reach us.
4. Multiply that travel time by the speed of light and you've got distance.

GPS satellite position

The basic orbits are quite exact but just to make things perfect the GPS satellites are constantly monitored by the Department of Defense.

They use very precise radar to check each satellite's exact altitude, position and speed.

The errors they're checking for are called "ephemeris errors" because they affect the satellite's orbit or "ephemeris." These errors are caused by gravitational pulls from the moon and sun and by the pressure of solar radiation on the satellites.

The errors are usually very slight but if you want great accuracy they must be taken into account.

GPS satellite position

- Satellites' orbital positions (ephemeris) are encapsulated within the transmitted messages.
- Ephemeris contain the parameters describing the orbital position of the satellites.
- The receiver uses these parameters to estimate satellites' positions.

GPS terms

- Ephemeris data gives the positions of naturally occurring astronomical objects as well as artificial satellites in the sky at a given time or times.
- Almanac contains information about the time and status of the entire satellite constellation.

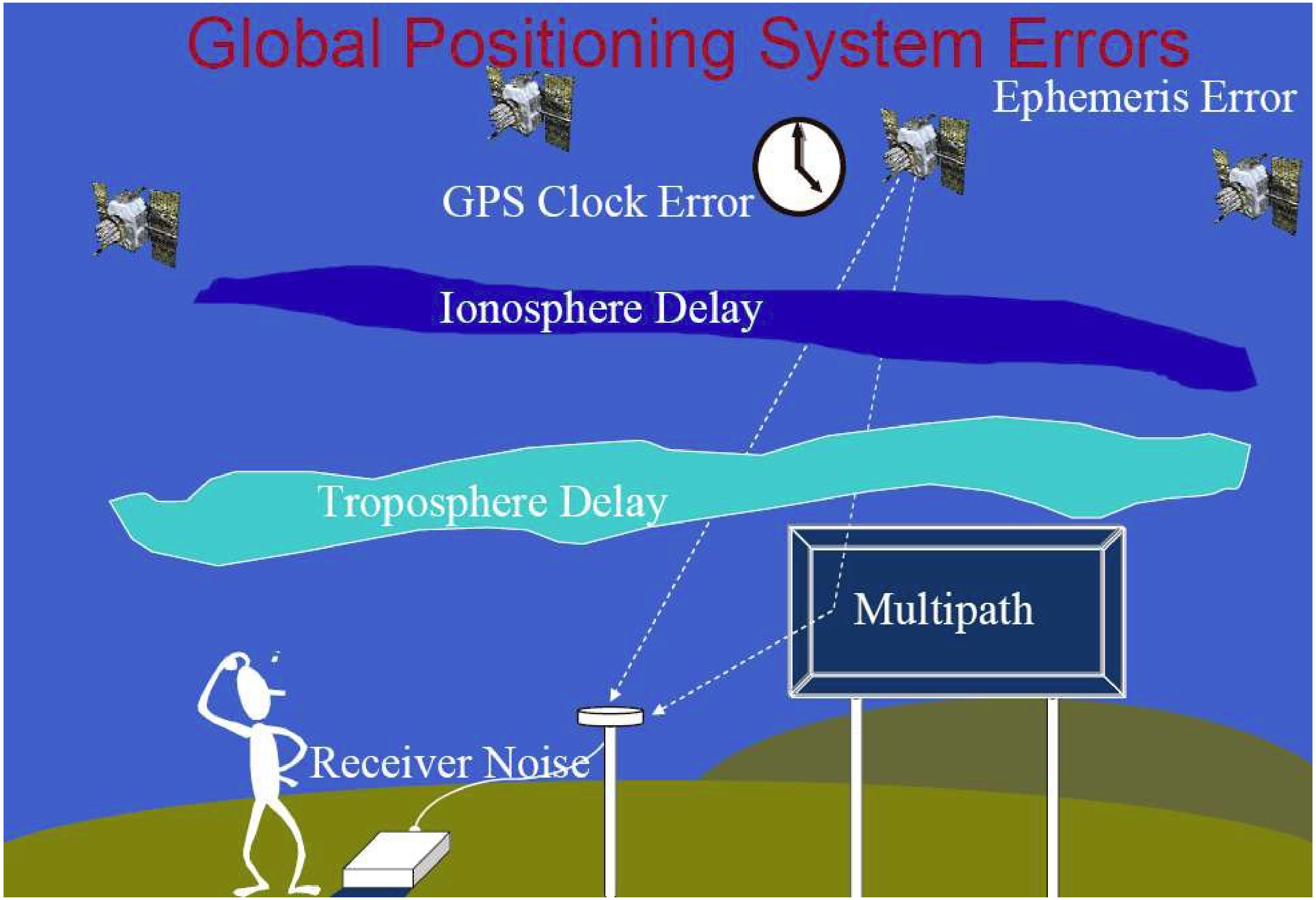
GPS trilateration (3D)

- 1 satellite – the position of the receiver could be a circle on the Earth surface (intersection between satellite sphere and earth sphere)
- 2 satellites – a circle in space, with 2 possible locations on Earth surface
- 3 satellites – two points, one possible location on Earth and one in space

No need for 4^{th} satellite, because Earth is the 4^{th} sphere

However, more satellites = more accuracy

GPS signal propagation problems



GPS signal errors

Standard Positioning Service (SPS) errors for civilian Users:

- Satellite clocks: 1.5 to 3.6 meters
- Orbital errors: < 1 meter
- Ionosphere: 5.0 to 7.0 meters
- Troposphere: 0.5 to 0.7 meters
- Receiver noise: 0.3 to 1.5 meters
- Multipath: 0.6 to 1.2 meters
- Selective Availability 100m

GPS position accuracy

Limited by two factors:

- Precision of distance measured to each GPS satellite
- How closely or far apart satellites are spaced across the sky

GPS satellite geometry factor is represented by Dilution Of Precision (DOP).

Higher DOP ~ greater error in the accuracy of position

Total error = uncertainty in satellite distance * DOP

GPS satellite geometry

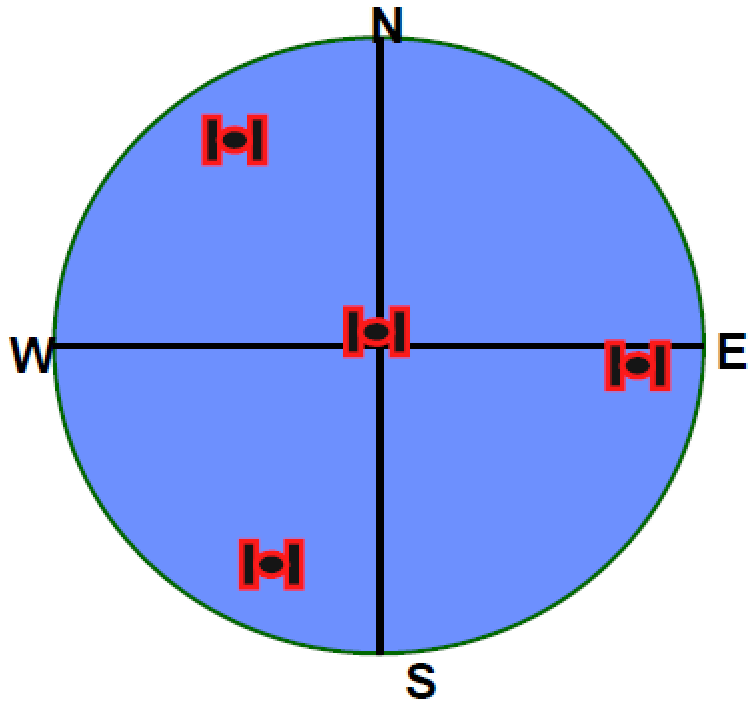
Dilution of Precision (DOP) indicates the relative arrangement of the satellites observed by the receiver

There are 5 kinds of DOP → Position Dilution of Precision (PDOP) is the most used one in order to indicate the accuracy of position estimation

The receiver will select the satellites in the best disposition.

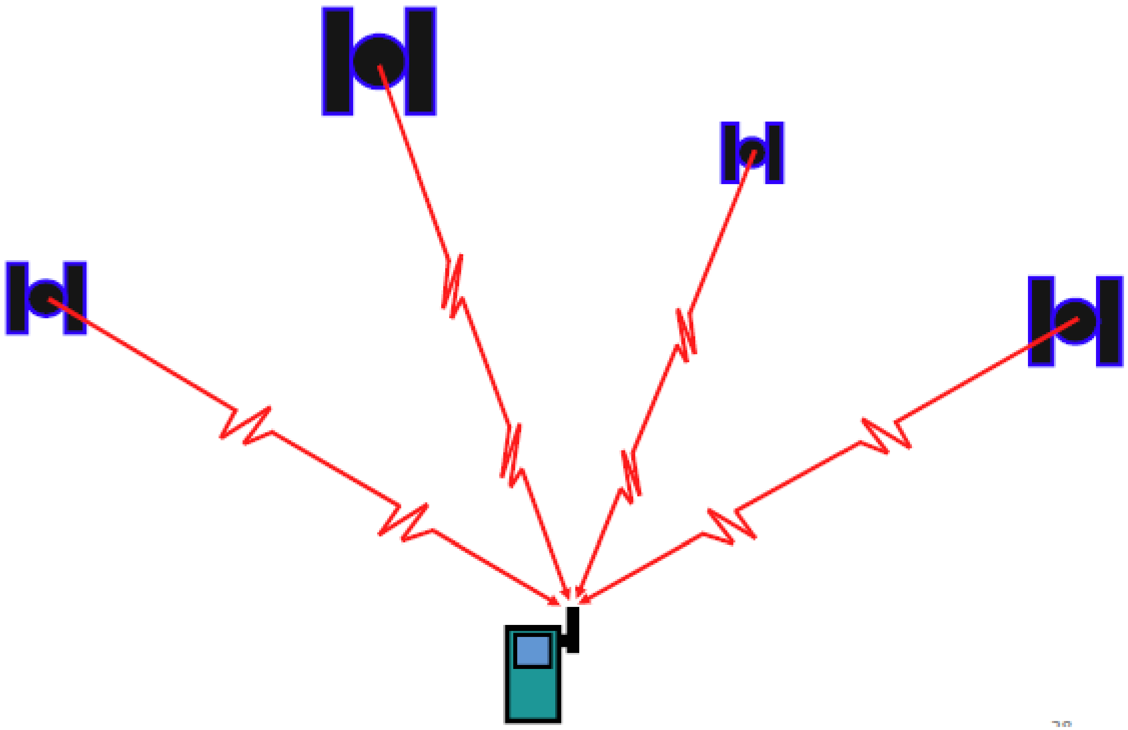
GPS satellite geometry

Ideal geometry: DOP <1



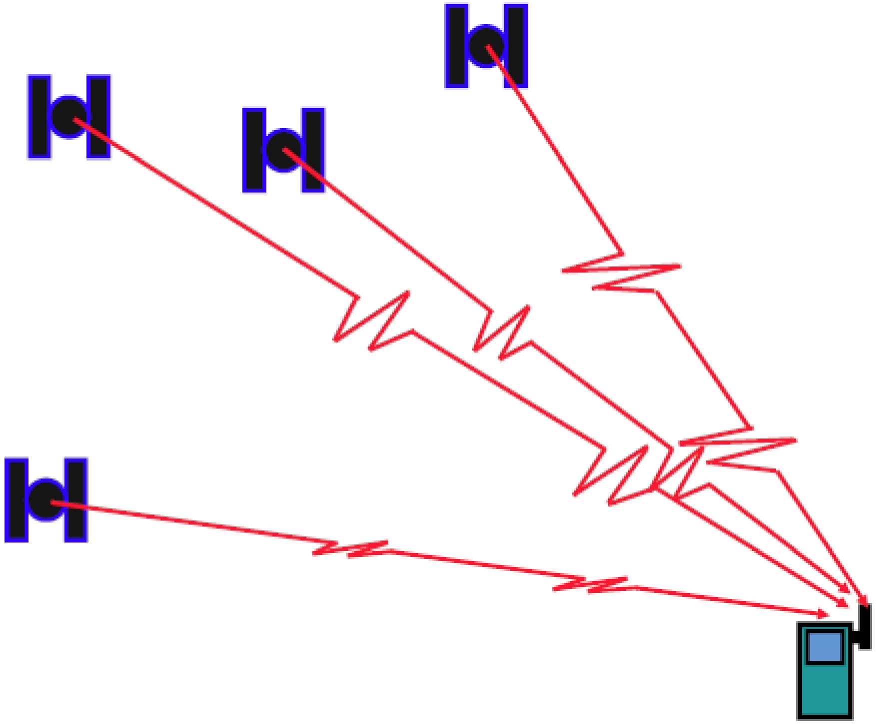
GPS satellite geometry

Good geometry: 2 < DOP < 5



GPS satellite geometry

Poor geometry: DOP > 20

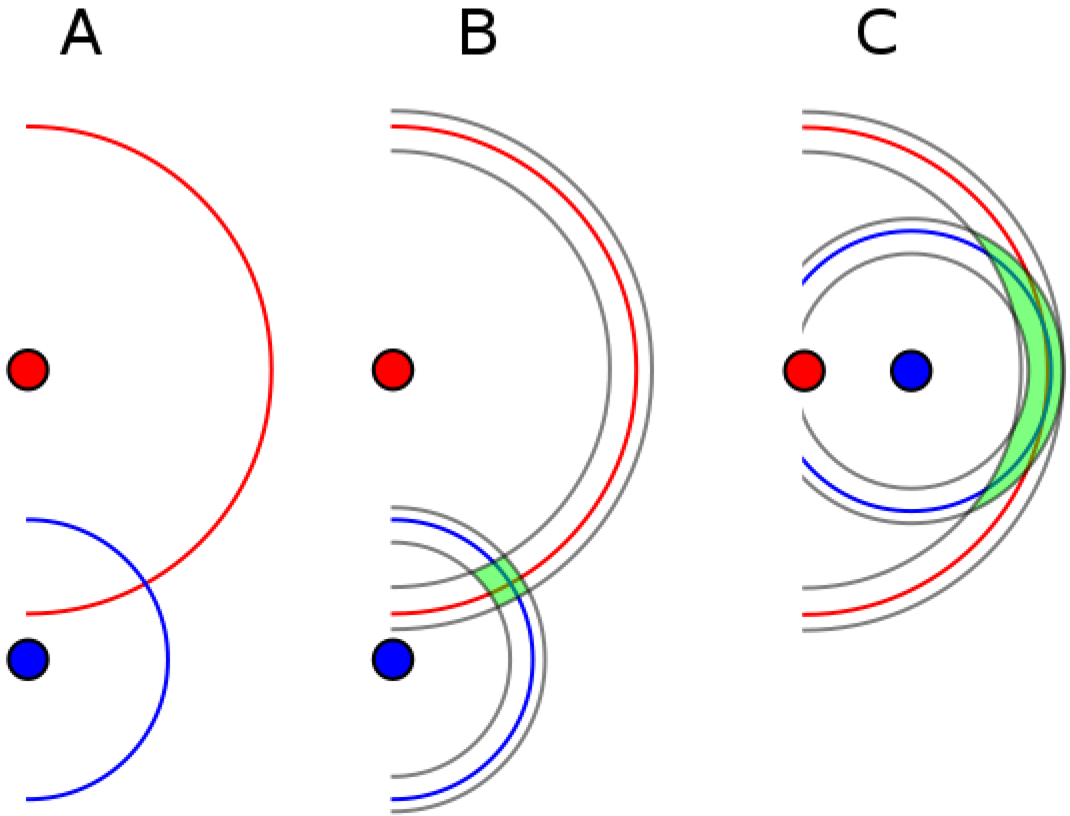


DOP example

A: measurement without errors

B: good positioning leads to slight error (green area)

C: poor positioning leads to increased error (green area)



GPS Information

GPS receivers compute the following, using data received from the satellites:

- Latitude & Longitude
- Altitude
- Speed
- Current time

GPS receivers can be integrated or external (serial, USB, Bluetooth)

GPS Information

The receiver provides applications with:

- Position, Velocity, Time, Altitude

Position formats:

degrees minutes seconds: 40° 26′ 46″ N, 79° 58′ 56″ W

degrees decimal minutes: 40° 26.767′ N, 79° 58.933′ W

decimal degrees: 40.446° N, 79.982° W

GPS Information

Data formats

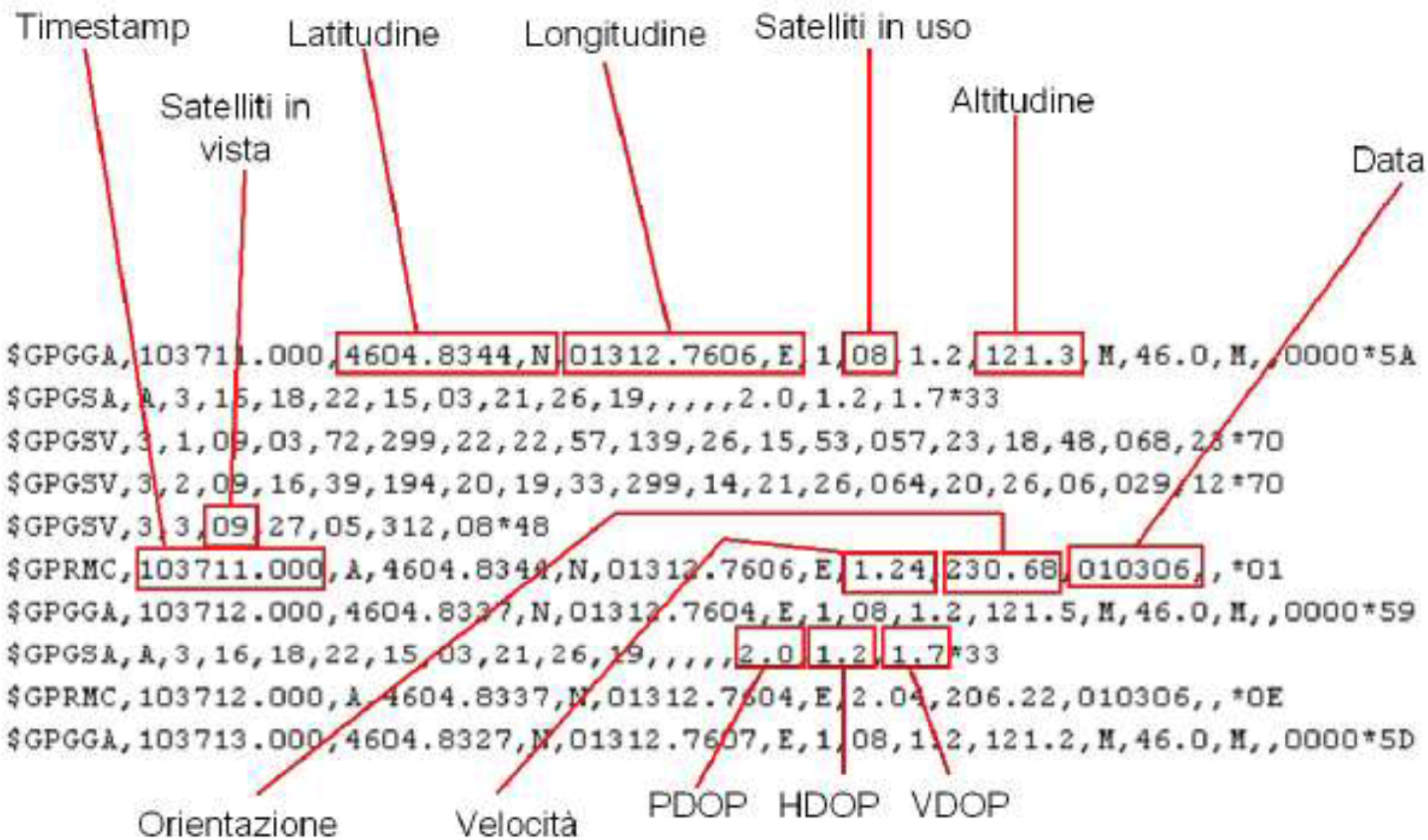
Position	
Latitude	ddmm.mmmm
Longitude	dddmm.mmmm
Altitude	m

Velocity	
Speed	knots
Heading	degrees

Time (UTC)	
Date	dd/mm/yy
Time	hh/mm/ss.sss

GPS Data Format

Defined by NMEA (National Marine Electronics Association)



GLONASS

Aka "Globalnaya Navigatsionnaya Sputnikovaya Sistema"

- Operated by Roscosmos
- Global coverage (1982–2016) with 24 satellites
- Precision of 4.5* – 7.4 m
- Orbit at 19,130 km

GLONASS

Works together with GPS!

→ Positions can be fixed more quickly and accurately

→ Smartphones use the same chipsets (2015) and receive GLONASS signals and positioning information along with GPS

→ Smartphone users receive a more accurate reception identifying location to within 2 meters (2012).

GLONASS

- 1976: development starts
- October 1982: first satellite launch
- 1995: constellation was complete, but degraded soon
- 2001: remade a government top priority
- 2010: GLONASS achieved 100% coverage of Russia
- October 2011: full orbital constellation of 24 satellites with global coverage

GLONASS ground control

The ground control segment is almost entirely located within former USSR (and several in Brazil)

The GLONASS ground segment consists of:

- 1 system control center (Krasnoznamensk ~ Moscow)
- 5 Telemetry, Tracking and Command centers
- 2 Laser Ranging Stations
- 10 Monitoring and Measuring Stations

GLONASS Receivers

https://en.wikipedia.org/wiki/GLONASS#Receivers

Include all modern smartphones: Samsung, Apple iPhone, HTC, LG, Motorola, Nokia, Sony, Huawei.

(Civilian) GPS vs GLONASS

2010: 2.0 – 8.76 m (6-11 satellites) vs. 4.5 – 7.4 m (7-8 satellites)

2011: GLONASS upgraded to accuracy of 2.8 m

2012 (combined): 2.4 – 4.7 m (14-19 satellites)

2012-2020: +16 GLONASS stations in Antarctica, Brazil, Indonesia → accuracy of 0.6 m

Galileo

Created by ESA (European Space Agency)

- Operated by ESA + EGNSS Agency
- Global coverage (2011-2020) with 24+6 satellites
- Precision of 1 m (public), 1 cm (encrypted)
- Orbit at 23,222 km
- 5BN euros
- Provides EU independence from GPS, GLONASS, BeiDou

Galileo advantages over GPS

Dependence (e.g. aviation) on GPS which uses Selective Availability (SA).

SA = intentional, time varying errors of up to 100m to the publicly available navigation signals, to deny an enemy the use of civilian GPS receivers for precision weapon guidance.

SA was disabled (software) in 2000, and newer hardware (2007) does not support it anymore.

Galileo Space segment

- 30 in-orbit spacecraft (24 in full service and 6 spares)
- Orbital altitude: 23,222 km
- 3 orbital planes, 56° inclination, ascending nodes separated by 120° longitude (8 operational satellites and 2 active spares per orbital plane)
- Satellite lifetime: >12 years
- Satellite mass: 675 kg

Galileo Ground segment

- 2 Ground Control Centers (Germany, Italy)
- 5 telemetry, tracking & control stations.
- Several worldwide distributed mission data uplink stations (ULS)
- Several worldwide distributed reference sensor stations (GSS)
- A data dissemination network between all geographically distributed locations

Galileo Services

Open access navigation: free for anyone with appropriate mass-market equipment; simple timing, and positioning down to 1 m.

Commercial navigation (encrypted): high precision (1cm), guaranteed service with fees.

Safety of life navigation: open service; for applications where guaranteed precision is essential.

Public regulated navigation (encrypted): continuous availability even if other services are disabled in time of crisis. Government agencies will be main users.

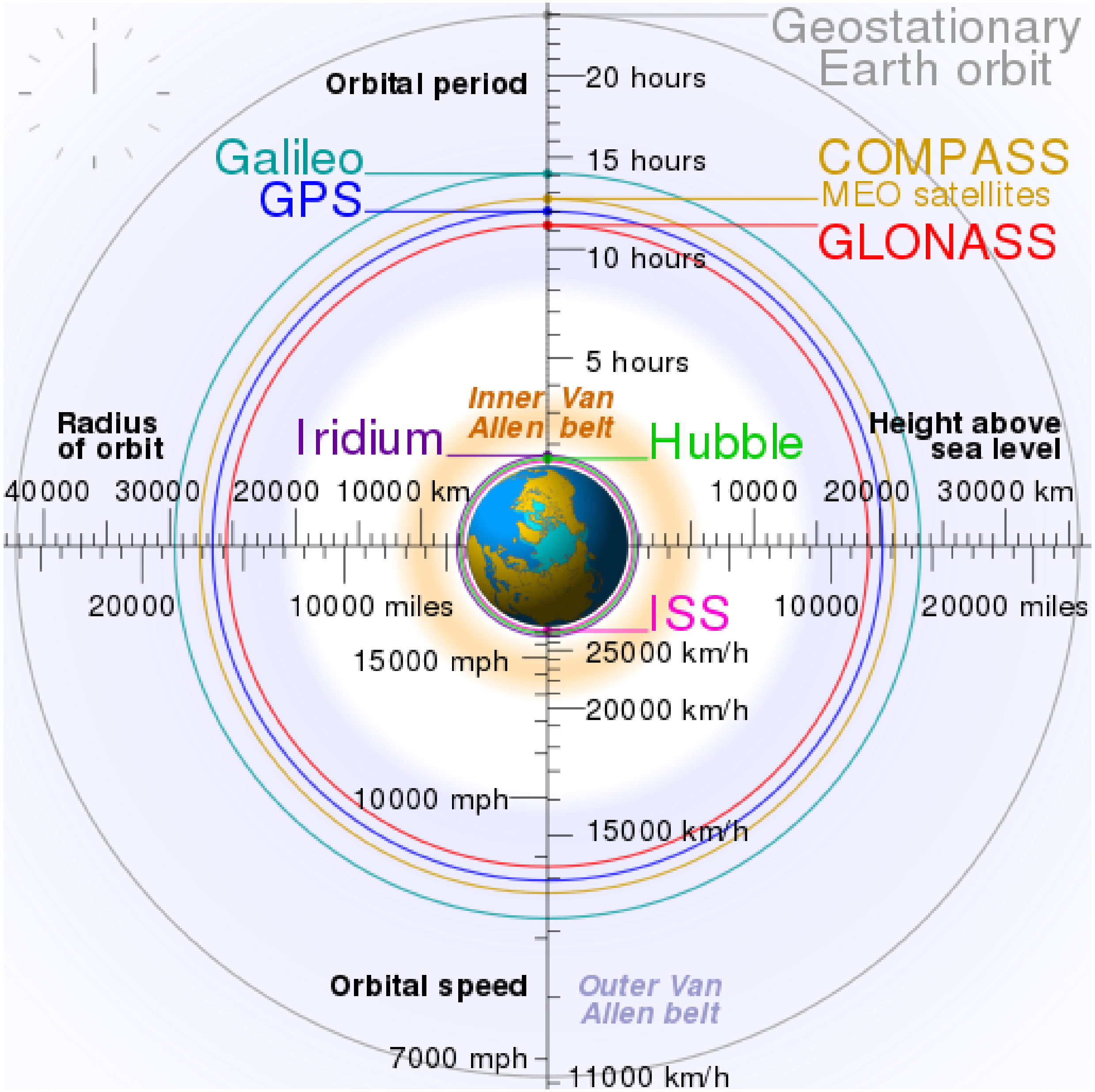
Search and rescue: system will pick up distress beacon locations; feasible to send feedback, e.g. confirming help is on its way.

BeiDou

Běidǒu ~ Big/Northern dipper (Carul mare)

Operated by Chinese CNSA

- Global coverage (2000 - 2012 (Pacific) - 2020)
- Constellation of 35 satellites (2nd generation BDS-2)
- Accuracy of 10m (public), 0.1m (encrypted)
- 2015: BDS-1 generating 31.5BN/year
- BDS-3 under way


Geostationary
Earth orbit
Orbital period
20 hours
15 hours
10 hours
5 hours
Galileo
GPS
COMPASS
MEO satellites
GLONASS
Inner Van
Allen belt
Iridium
Hubble
Radius
of orbit
Height above
sea level
40000 30000 20000 10000 km
10000 20000 30000 km
20000 10000 miles
10000 20000 miles
ISS
15000 mph
25000 km/h
20000 km/h
10000 mph
15000 km/h
Orbital speed
Outer Van
Allen belt
7000 mph
11000 km/h

Programming GPS Applications

GPS Serial port

- The GPS receiver is connected through serial communication to CPU – hardware COM
- GPS intermediate driver – allows multiple applications to share the GPS receiver – software COM

Location Manager

- High level abstraction
- Register and listen for positioning data

Location Manager

Smart mobile devices support multiple techniques for position estimation:

- Cell ID
- WiFi
- Network – triangulation by network provider
- GNSS (GPS, GLONASS)

Cell ID

Use the position of the GSM cell where the mobile is currently connected.

- Every GSM cell knows its position (has a GPS)
- The cell positions are available to mobile applications
- Low accuracy – 2 km

Location Manager on Android OS

- NETWORK_PROVIDER, GPS_PROVIDER
- LocationManager class
- Interface, listeners, callback functions

```
locationManager.requestLocationUpdates(LocationManager.
NETWORK_PROVIDER, min_time, min_distance,
locationListener);
```

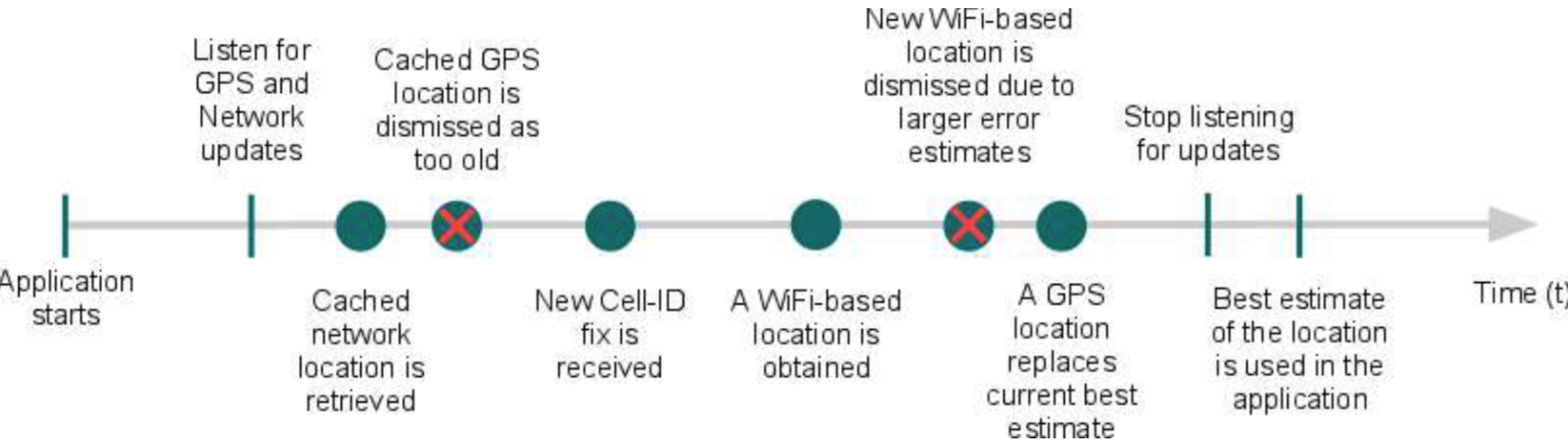
```
LocationListener: onLocationChanged(Location location)
```

Location Accuracy Tradeoff

Position estimation algorithms implemented by applications should consider:

1. Several position providers (e.g. GPS & network)
2. Accuracy of signals
3. Delay in receiving location updates
4. Rate of updates
5. Power consumption generated on device
6. User mobility (will the user move a lot?)
7. Tradeoff between accuracy and time
8. How to estimate position from more recent positioning data having lower accuracy?

Positioning Algorithm example



Java code examples – initialize listeners

onCreate:

```
LocationManager locationManager = (LocationManager) getSystemService(LOCATION_SERVICE);

LocationListener locationListenerGPS = new LocationListener() {
    @Override
    public void onLocationChanged(Location location) {
        double lat = location.getLatitude();
        double lng = location.getLongitude();

        Geocoder geoCoder = new Geocoder(UserProfileActivity.this, Locale.ENGLISH);
        List<Address> address = geoCoder.getFromLocation(lat, lng, 1);
        // … do something with address(es)
    }
    @Override
    public void onStatusChanged(String s, int i, Bundle bundle) {
    }
    @Override
    public void onProviderEnabled(String s) {
    }
    @Override
    public void onProviderDisabled(String s) {
    }
};
```

Java code examples – attach listeners

GPS or NETWORK

NETWORK only

```
@Override
protected void onResume() {
    super.onResume();

    if (Build.VERSION.SDK_INT >= Build.VERSION_CODES.M) {
        if (checkSelfPermission(Manifest.permission.ACCESS_FINE_LOCATION) == PackageManager.PERMISSION_GRANTED ||
                checkSelfPermission(Manifest.permission.ACCESS_COARSE_LOCATION) == PackageManager.PERMISSION_GRANTED)
{
            Location lastLocation = null;

            for (String provider : locationManager.getAllProviders()) {
                if (locationManager.getLastKnownLocation(provider) != null) {
                    lastLocation = locationManager.getLastKnownLocation(provider);
                }
            }

            if (lastLocation != null)
                checkLocation(lastLocation);
            else {
                locationManager.requestLocationUpdates(LocationManager.GPS_PROVIDER, 0, 0, locationListenerGPS);
                locationManager.requestLocationUpdates(LocationManager.NETWORK_PROVIDER, 0, 0,
                        locationListenerNetwork);
            }
        }
    } else {
        locationManager.requestLocationUpdates(LocationManager.GPS_PROVIDER, 0, 0, locationListenerGPS);
        locationManager.requestLocationUpdates(LocationManager.NETWORK_PROVIDER, 0, 0, locationListenerNetwork);
    }
}
```

Java code examples – detach listeners

```
@Override
protected void onPause() {
    super.onPause();
    locationManager.removeUpdates(locationListenerGPS);
    locationManager.removeUpdates(locationListenerNetwork);
}
```