MOBILE COMPUTING

CSE 40814/60814
Spring 2021

Location, Location, Location

- Location information adds "context" to activity:
  - location of sensed events in the physical world
  - location-aware services
  - location often primary sensor information (supply chain management, surveillance)
  - object tracking
  - coverage area management
  - geo-tagging
- Location often not known a priori, therefore, localization is the task of determining the position (e.g., coordinates) of a device or the spatial relationships among objects

Overview

- Global position
  - position within general global reference frame
  - Global Positioning System or GPS (longitudes, latitudes)
  - Universal Transverse Mercator or UTM (zones and latitude bands)
- Relative position
  - based on arbitrary coordinate systems and reference frames
  - distances between nodes (no relationship to global coordinates)
- Accuracy versus precision
  - GPS: true within 10m for 90% of all measurements
    - accuracy: 10m ("how close is the reading to the ground truth?")
    - precision: 90% ("how consistent are the readings?")
- Symbolic position information
  - "office 354"
  - "mile marker 17 on Highway 23"

High accuracy,
Low precision

Low accuracy,
High precision

Ranging Techniques

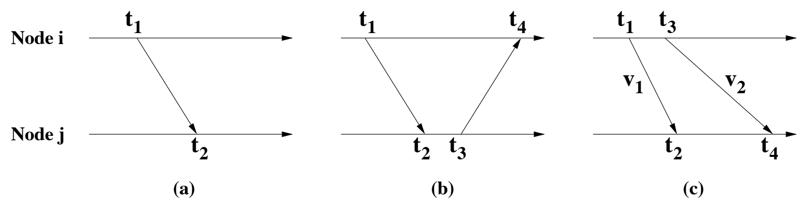
- Time of Arrival (ToA, time of flight)
  - distance between sender and receiver of a signal can be determined using the measured signal propagation time and known signal velocity
  - sound waves: 343m/s, i.e., approx. 30ms to travel 10m
  - radio signals: 300km/s, i.e., approx. 30ns to travel 10m
- One-way ToA
  - one-way propagation of signal
  - requires highly accurate synchronization of sender and receiver clocks

$$dist_{ij} = (t_2 - t_1) * v$$

- Two-way ToA
  - round-trip time of signal is measured at sender device
  - third message if receiver wants to know the distance

$$dist_{ij} = \frac{(t_4 - t_1) - (t_3 - t_2)}{2} * v$$

Ranging Techniques



- Time Difference of Arrival (TDoA)
  - two signals with different velocities
  - example: radio signal (sent at t_1 and received at t_2), followed by acoustic signal (sent at $t_3=t_1+t_{wait}$ and received at t_4)
  - no clock synchronization required
  - distance measurements can be very accurate
  - need for additional hardware

Ranging Techniques

- Angle of Arrival (AoA)
  - direction of signal propagation
  - typically achieved using an array of antennas or microphones
  - angle between signal and some reference is orientation
  - spatial separation of antennas or microphones leads to differences in arrival times, amplitudes, and phases
  - accuracy can be high (within a few degrees)
  - adds significant hardware cost

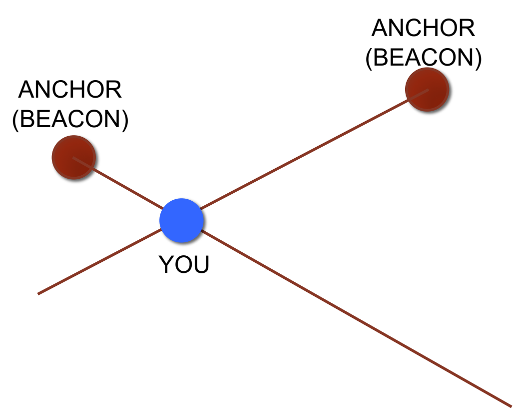
Ranging Techniques

- Received Signal Strength (RSS)
  - signal decays with distance
  - many devices measure signal strength with received signal strength indicator (RSSI)
    - vendor-specific interpretation and representation
    - typical RSSI values are in range of 0..RSSI_Max
    - common values for RSSI_Max: 100, 128, 256
  - in free space, RSS degrades with square of distance
  - expressed by Friis transmission equation

$$\frac{P_r}{P_t} = G_t G_r \frac{\lambda^2}{(4\pi)^2 R^2}$$

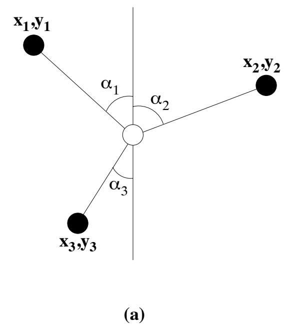
  - in practice, the actual attenuation depends on multipath propagation effects, reflections, noise, etc.
  - realistic models replace R^2 with R^n ($n=3..5$)

Triangulation

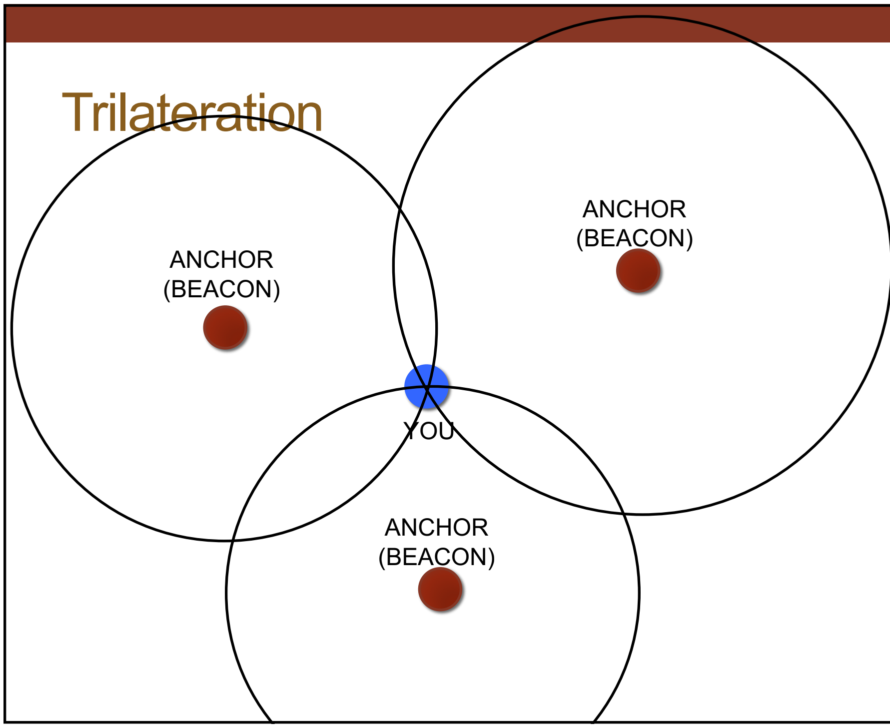


Triangulation

- Example of range-based localization
- Uses the geometric properties of triangles to estimate location
- Relies on angle (bearing) measurements
- Minimum of two bearing lines (and the locations of anchor nodes or the distance between them) are needed for two-dimensional space

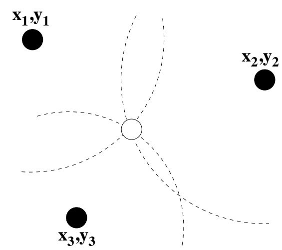


Trilateration



Trilateration

- Localization based on measured distances between a node and a number of anchor points with known locations
- Basic concept: given the distance to an anchor, it is known that the node must be along the circumference of a circle centered at anchor and a radius equal to the node-anchor distance
- In two-dimensional space, at least three non-collinear anchors are needed and in three-dimensional space, at least four non-coplanar anchors are needed



(b)

Trilateration*

- n anchor nodes: $\mathbf{x_i}=(x_i,y_i)$ (i=1..n)
- Unknown node location $\mathbf{x}=(x,y)$
- Distances between node and anchors known (r_i, i=1..n)
- Relationships between anchor/node positions and distances (2 dimensions):

$$\begin{bmatrix} (x_1-x)^2+(y_1-y)^2 \\ (x_2-x)^2+(y_2-y)^2 \\ \vdots \\ (x_n-x)^2+(y_n-y)^2 \end{bmatrix} = \begin{bmatrix} r_1^2 \\ r_2^2 \\ \vdots \\ r_n^2 \end{bmatrix}$$

- This can be represented as $A\mathbf{x}=b$ with:

$$A = \begin{bmatrix} 2(x_n-x_1) & 2(y_n-y_1) \\ 2(x_n-x_2) & 2(y_n-y_2) \\ \vdots & \vdots \\ 2(x_n-x_{n-1}) & 2(y_n-y_{n-1}) \end{bmatrix} \quad b = \begin{bmatrix} r_1^2-r_n^2-x_1^2-y_1^2+x_n^2+y_n^2 \\ r_2^2-r_n^2-x_2^2-y_2^2+x_n^2+y_n^2 \\ \vdots \\ r_{n-1}^2-r_n^2-x_{n-1}^2-y_{n-1}^2+x_n^2+y_n^2 \end{bmatrix}$$

Trilateration*

- Based on this least squares system, we can obtain estimation of position (x,y) using $\mathbf{x}=(A^TA)^{-1}A^Tb$
- Anchor positions and distance measurements are inaccurate, therefore, if they are based on Gaussian distributions, we can assign a weight to each equation *i*:

$$w_i = 1/\sqrt{\sigma^2_{\text{distance}_i} + \sigma^2_{\text{position}_i}} \qquad \sigma^2_{\text{position}_i} = \sigma_{x_i}{}^2 + \sigma_{y_i}{}^2$$

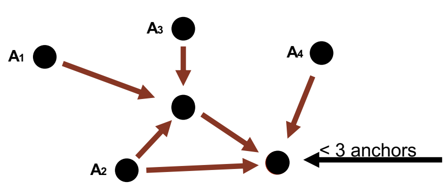
- The least squares system is then again $A\mathbf{x}=b$ with:

$$A = \begin{bmatrix} 2(x_n - x_1)\times w_1 & 2(y_n - y_1)\times w_1 \\ 2(x_n - x_2)\times w_2 & 2(y_n - y_2)\times w_2 \\ \vdots & \vdots \\ 2(x_n - x_{n-1})\times w_{n-1} & 2(y_n - y_{n-1})\times w_{n-1} \end{bmatrix} \quad b = \begin{bmatrix} (r_1^2 - r_n^2 - x_1^2 - y_1^2 + x_n^2 + y_n^2)\times w_1 \\ (r_2^2 - r_n^2 - x_2^2 - y_2^2 + x_n^2 + y_n^2)\times w_2 \\ \vdots \\ (r_{n-1}^2 - r_n^2 - x_{n-1}^2 - y_{n-1}^2 + x_n^2 + y_n^2)\times w_{n-1} \end{bmatrix}$$

- The covariance matrix of **x** is then $Cov_x=(A^TA)^{-1}$

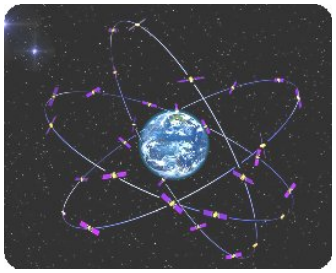
Iterative Multilateration

- Problem: *what if node does not have at least three neighboring anchors?*
- Solution: once a node has determined its position, it becomes an anchor
- Iterative multilateration:
  - repeats until all nodes have been localized
  - error accumulates with each iteration



GPS - Background

- Mariners relied upon the sun for latitude, and clocks for longitude
- With the launch of Sputnik in 1957, radio-based global positioning became a (theoretical) possibility



GPS - Background

- This was a very crude form of GPS using only **one satellite** (1960s)
  - Doppler shift for distance measurement
  - Submarines used it
  - Could only be used every 35-45 minutes
  - Submarines had to be non-moving
- US systems: TRANSIT, Timation
- Major innovation was the inclusion of an atomic clock
- Submarines could now be in motion and use the system (but about an hour to get a fix)

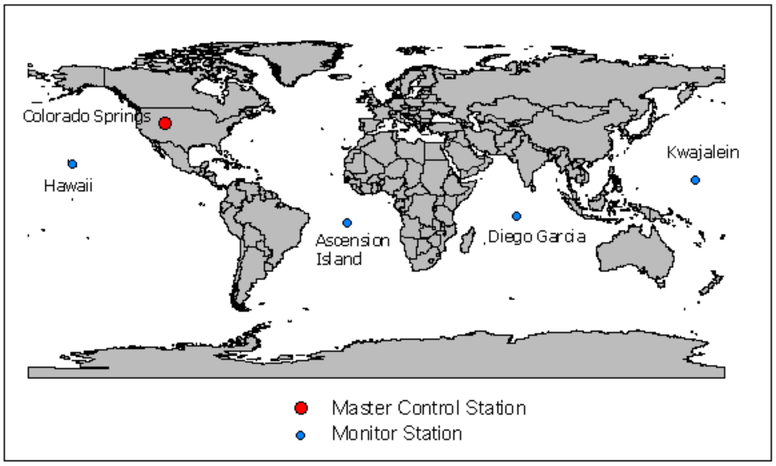
GPS-Based Localization

- Global Positioning System
  - most widely publicized location-sensing system
  - provides lateration framework for determining geographic positions
  - originally established as NAVSTAR (Navigation Satellite Timing and Ranging)
  - example of global navigation satellite system (GNSS)
  - consists of at least 24 satellites orbiting at approx. 11,000 miles
  - started in 1973, fully operational in 1995
- Two levels of service:
  - Standard Positioning Service (SPS)
    - available to all users, no restrictions or direct charge
    - high-quality receivers have accuracies of 3m and better horizontally
  - Precise Positioning Service (PPS)
    - used by US and Allied military users
    - uses two signals to reduce transmission errors

GPS-Based Localization

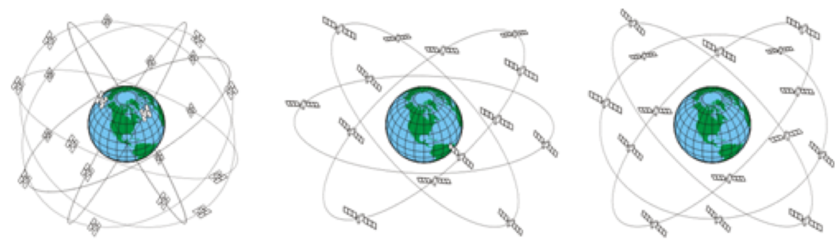
- Satellites are uniformly distributed in **six orbits (4 satellites per orbit)**
- Satellites circle earth twice a day at approx. 7000 miles/hour
- At least 8 satellites can be seen simultaneously from almost anywhere
- Each satellite broadcasts coded **radio waves (pseudorandom code)** over frequency 1575.42 MHz, containing
  - identity of satellite
  - location of satellite
  - the satellite's status
  - date and time when signal was sent
- Several monitor stations constantly receive satellite data and forward data to a master control station (MCS)
- MCS is located near Colorado Springs, Colorado
- MCS uses the data from monitor stations to compute corrections to the satellites' orbital and clock information which are sent back to the satellites

Monitor Stations



Satellites and orbits

Comparison of GNSS

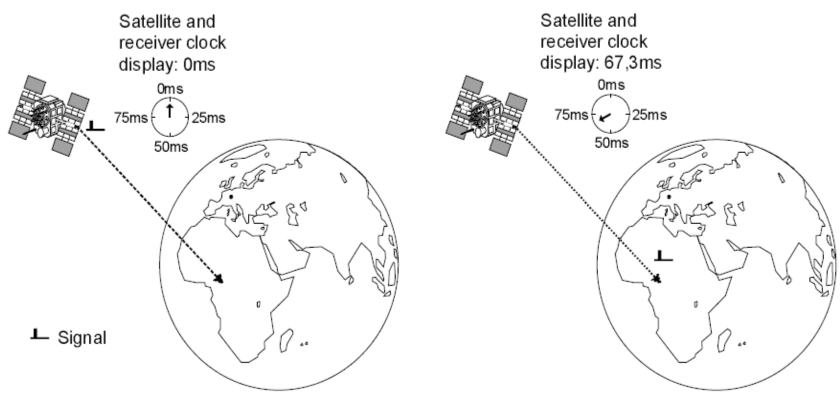


GPS
- 6 Orbital planes
- 24 Satellites + Spare
- 55° Inclination Angle
- Altitude 20,200km

Galileo
- 3 Orbital planes
- 27 Satellites + 3 Spares
- 56° Inclination Angle
- Altitude 23,616km

GLONASS
- 3 Orbital planes
- 21 Satellites + 3 Spares
- 64.8° Inclination Angle
- Altitude 19,100km

Distance Measurement (Ranging)

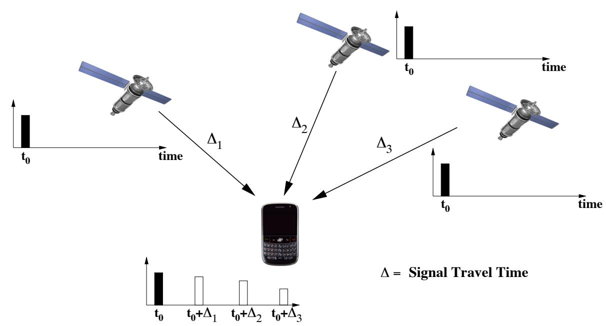


Signal transmition (start time)

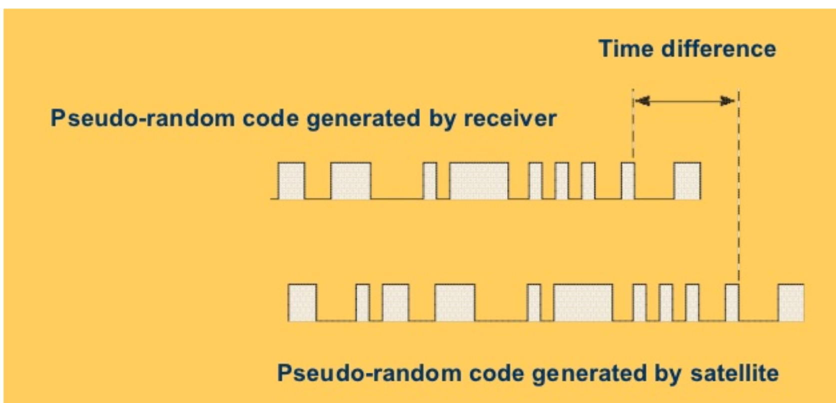
Signal reception (stop time)

GPS-Based Localization

- Satellites and receivers use accurate and synchronized clocks
- Receiver compares generated code with received code to determine
  - the actual code generation time of the satellite
  - time difference Δ between code generation time and current time
  - Δ expresses the travel time of the code from satellite to receiver



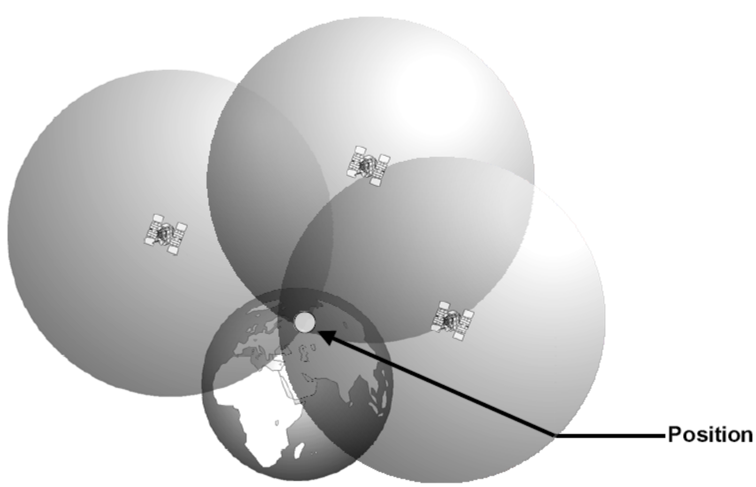
GPS-Based Localization



GPS-Based Localization

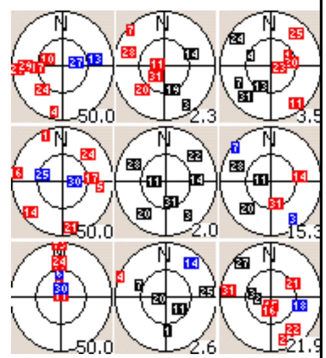
- Radio waves travel at the speed of light (approx. 186,000 miles/second)
- With known Δ, the distance can be determined
- Receiver knows that it is located somewhere on a sphere centered on the satellite with a radius equal to this distance
- With three satellites, the location can be narrowed down to two points
  - typically one of these two points can be eliminated easily
- With four satellites, accurate localization is possible
  - accurate positioning relies on accurate timing
  - receiver clocks are much less accurate than atomic GPS clocks
  - small timing errors lead to large position errors
    - example: clock error of 1ms translates to a position error of 300km
  - fourth sphere would ideally intersect with all three other spheres in one exact location
  - spheres too large: reduce them by adjusting the clock (moving it forward)
  - spheres too small: increase them by adjusting the clock (moving it backward)

GPS Trilateration



GPS Signals

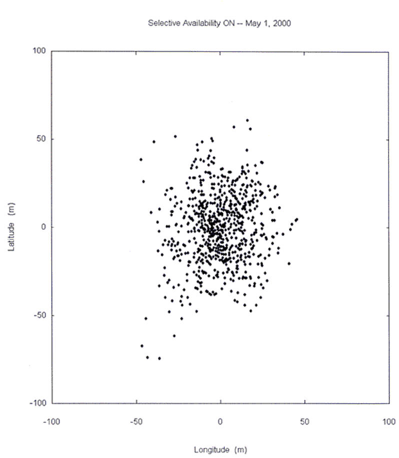
- GPS operates 24/7 and is unaffected by cloud, rain, dark
- BUT signals are weak– limited signals indoors, under trees, in bags!
- Getting **position fix** means seeing > 3 satellites in part of sky you can see
- As you move, visible satellites change
- Signals reflect off buildings leading to 'multipath' error
- Accuracy under ideal conditions with consumer devices= 5-10m
- "Sat nav" systems snap positions to roads

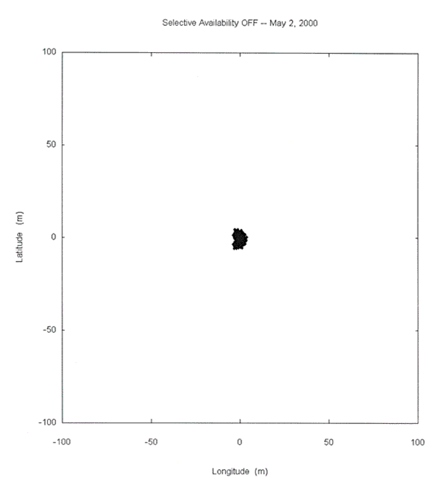


Outer circle= horizon, squares are satellites. Red=blocked, Blue= fixing, black= fixed. Values are DOP quality of fix.

Deliberately Introduced Error

- Turned off in 2000 (errors up to 100m)

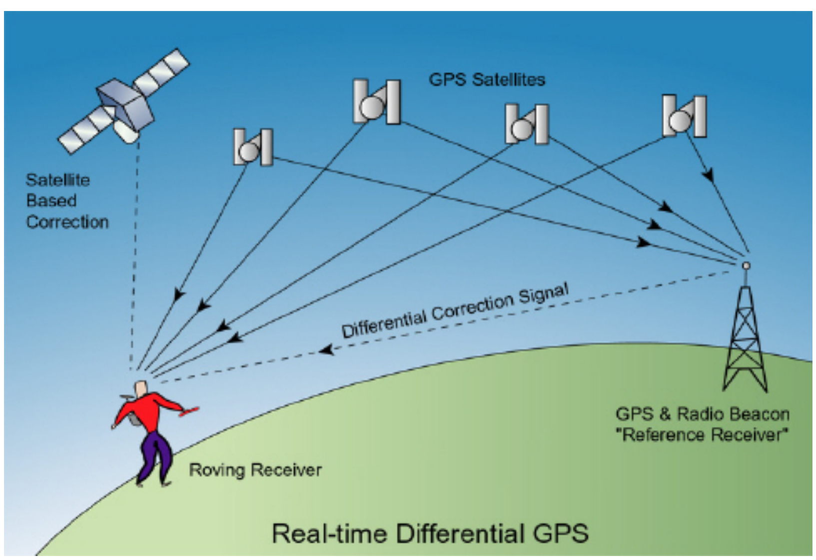




GPS-Based Localization

- Most GPS receivers today can achieve good accuracy (e.g., 10m-15m or better)
- Additional advanced techniques can be used to further improve accuracy:
  - example: Differential GPS (DGPS)
    - relies on land-based receivers with exactly known locations
    - they receive signals, compute correction factors, and broadcast them to GPS receivers
    - GPS receivers correct their own measurements
    - improves location accuracy from say 15m to 10cm

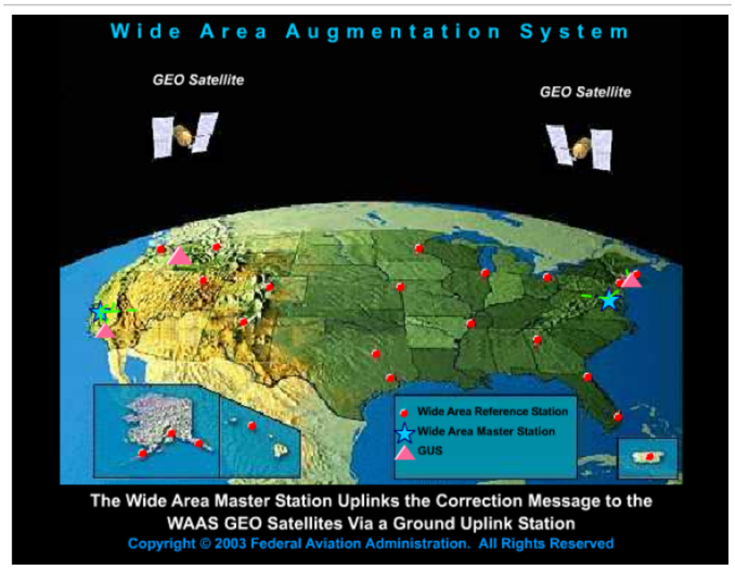
Differential GPS



Wide Area Augmentation System (WAAS)

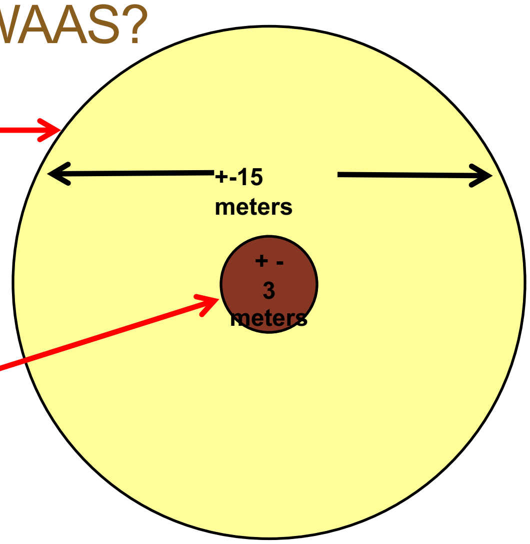
- **Error correction system** that uses reference ground stations
- 25 reference stations in US
- Monitor GPS and send correction values to two geo-stationary satellites
- The **two geo-stationary satellites** broadcast back to Earth on GPS L1 frequency (1575.42MHz)
- **Only available in North America**, WAAS enabled GPS receiver needed

WAAS



How Good Is WAAS?

With Selective Availability set to zero, and under ideal conditions, a GPS receiver without WAAS can achieve fifteen meter accuracy most of the time.*

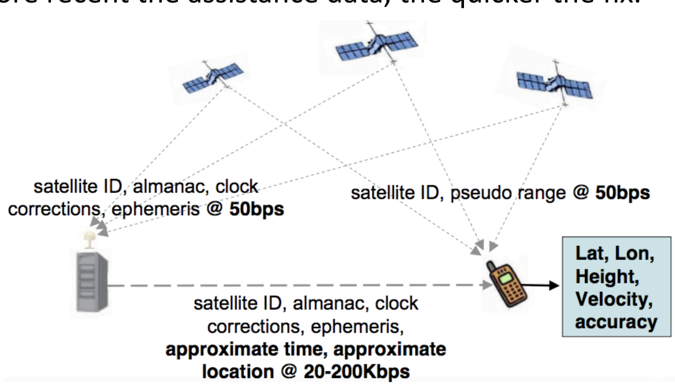


Under ideal conditions a WAAS equipped GPS receiver can achieve three meter accuracy 95% of the time.*

* Precision depends on good satellite geometry, open sky view, and no user induced errors.

A-GPS

- GPS needs to get data from satellites to calibrate the position-fixing codes, can take a minute ("time-to-first-fix").
- This data can be supplied over mobile web cutting time to first fix to a few seconds: this is called assisted GPS.
- The more recent the assistance data, the quicker the fix.



A-GPS

- Assisted GPS gives improvements in
  - Time to First Fix
  - Battery Life
  - Sensitivity
  - Cost

- Assistance Data
  - Satellite Position
  - Time information
  - Visible GPS List
  - Sensitivity