CSCE 438/838: Internet of Things

Localization

Why Localization?

- People tracking
- Track items (boxes in a warehouse, badges in a building, etc)
- Identify items (the thermostat in the corner office)
- Not everything needs an IP address
- GPS does not work everywhere
- Smart Systems – devices need to know where they are
- Geographic routing & coverage problems

Localization Challenges

- PHY Layer Measurement Errors
- Computational Constraints
- Lack of GPS Data
- Low-end Sensor Devices
- Scalability, robustness, and accuracy based on applications

Localization Challenges: PHY Layer Measurements

- Multipath, shadowing and sensor imperfections affect signal propagation properties
- -> False distance calculations & incorrect angles

Localization Challenges: Computational Constraints

- Local information (distance, angle or connectivity) from several end-points are combined to provide location estimates
- Multiple measurements are needed to minimize erroneous information
- Many formalizations of the localization problems require high processing power and memory
- (e.g., how to solve the optimization problem)

Localization Challenges: Lack of GPS

- High costs
- High energy consumption
- Not useful for many applications (in-door, confined areas etc)
- NOTE:
- GPS equipped sensors can still be used as ANCHOR (BEACON) nodes in localization algorithms

Localization Challenges: Low-end Sensor Devices

- Sensors have low-end components for low-cost production
- Measurement hardware (low-end clock crystals) on sensors can introduce errors in distance or angle estimations

GPS

- Global Positioning System

- History
  - U.S. Department of Defense wanted the military to have a super precise form of worldwide positioning
  - After $12B, the result was the GPS system!

Credit: US Naval Observatory

GPS

- Approach
  - “Man-made stars" as reference points to calculate positions accurate to a matter of meters
  - Like giving every square meter on EARTH a unique address!

Where are the Satellites?

- Need to know exactly where the satellites are
- Each GPS satellite has a very precise orbit, 11,000 miles up in space, according to the GPS master Plan
- On the ground all GPS receivers have an almanac programmed into their computers that tells them where in the sky each satellite is, moment by moment

GPS - CONSTELLATION

- Three major segments:
  - Space segment (SS)
  - Control segment (CS)
  - User segment (US)

SPACE SEGMENT

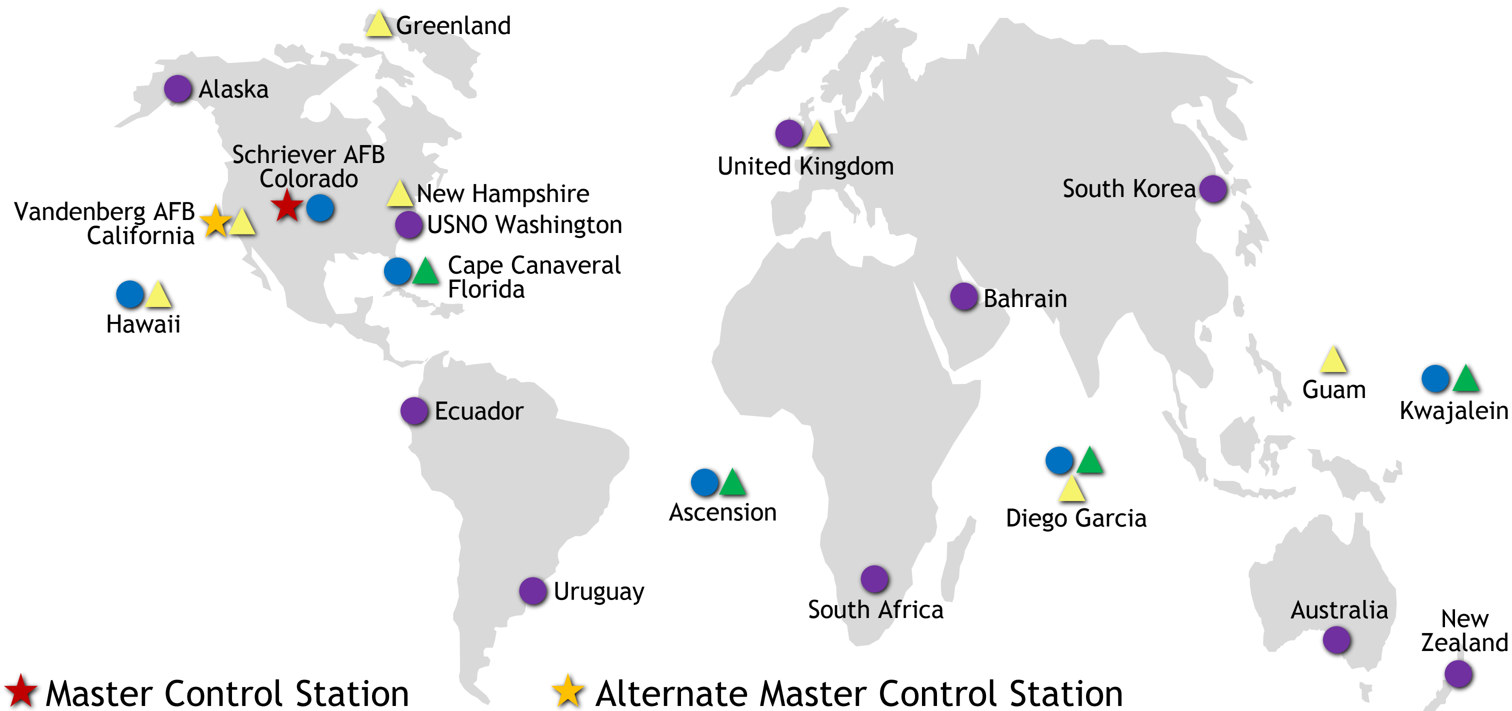
- Composed of the orbiting GPS satellites, or Space Vehicles (SV)
- Constellation design to provide coverage, availability
  - Originally 24 SVs, eight each in three circular orbital planes
  - Later six planes with four satellites in each
  - Orbits are arranged so that at least six satellites are always within line of sight from almost everywhere on Earth's surface
- Satellite Ranging Signal and Navigation/Timing Data

NovAtel Inc., An Introduction to GNSS, 2nd edition

Control Segment

- Monitor the GPS satellites, checking both their operational health and their exact position in space
  - A Master Control Station (MCS)
  - An Alternate Master Control Station
- Network of ground monitoring stations
  - Four dedicated Ground Antennas (Kwajalein, Ascension Island, Diego Garcia, and Cape Canaveral)
  - Six dedicated Monitor Stations (Hawaii, Kwajalein, Ascension Island, Diego Garcia, Colorado Springs, and Cape Canaveral)
- Orbit and Satellite clocks estimation
- Command and Control uplink capabilities

GPS Control Segment



- Master Control Station
- Ground Antenna
- Air Force Monitor Station
- Alternate Master Control Station
- AFSCN Remote Tracking Station
- NGA Monitor Station

User Segment

- Secure Military User Equipment (MUE)
- Civil application user equipment (CUE)
- Hundreds of thousands of U.S. and allied military users of the secure GPS Precise Positioning Service
- Tens of millions of civil, commercial and scientific users of the Standard Positioning Service

How GPS Works

- 1. The basis of GPS is "trilateration" from satellites. (popularly but wrongly called "triangulation")
- 2. To "trilaterate," a GPS receiver measures distance using the travel time of radio signals.
- 3. To measure travel time, GPS needs very accurate timing which it achieves with some tricks.

How GPS Works

- 4. Along with distance, you need to know exactly where the satellites are in space. High orbits and careful monitoring are the secret.
- 5. Finally you must correct for any delays the signal experiences as it travels through the atmosphere.

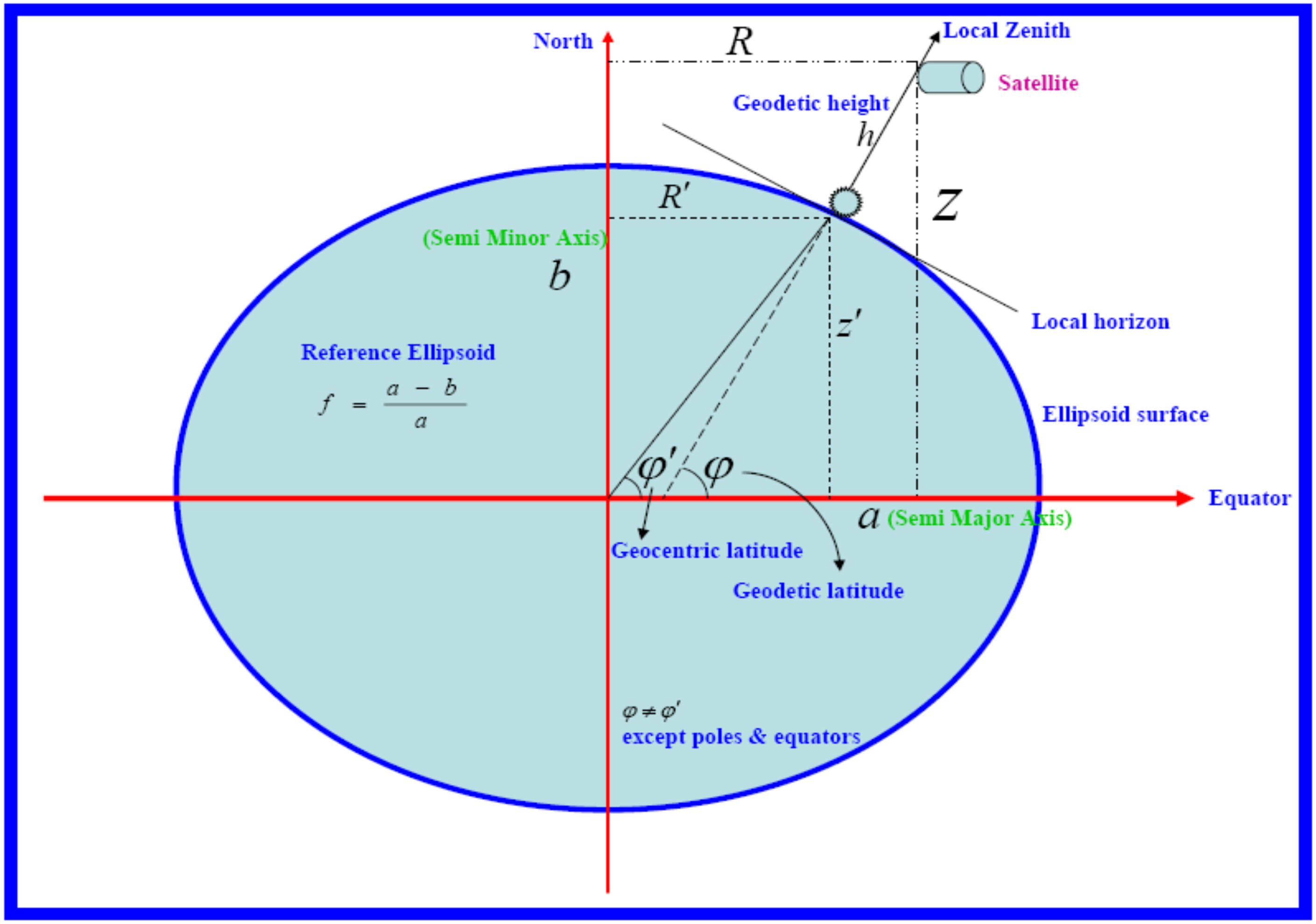
GPS Navigation and Timing

- Each GPS satellite carries an Atomic clock that is precisely synchronized to a common internal navigation time scale
- Each satellite broadcasts its precise position in space
- A GPS receiver records the time difference between the receiver clock and the transmitted satellite clock, which provides a measure of distance between the user and the satellite
- These time difference measurements, used with knowledge of the satellite's position, allow the user to solve for the user-unknown position and time
- Four satellites are required to compute the four dimensions of X, Y, Z (position) and Time.

EARTH-based Coordinate System

- Earth's surface is approximated by an ellipsoid
- Locations near the surface are described in terms of latitude, longitude and height

GPS



Remarks:

Local Zenith:

- direction away from the poles on Earth's surface proportional to local horizon

On Sphere: direction

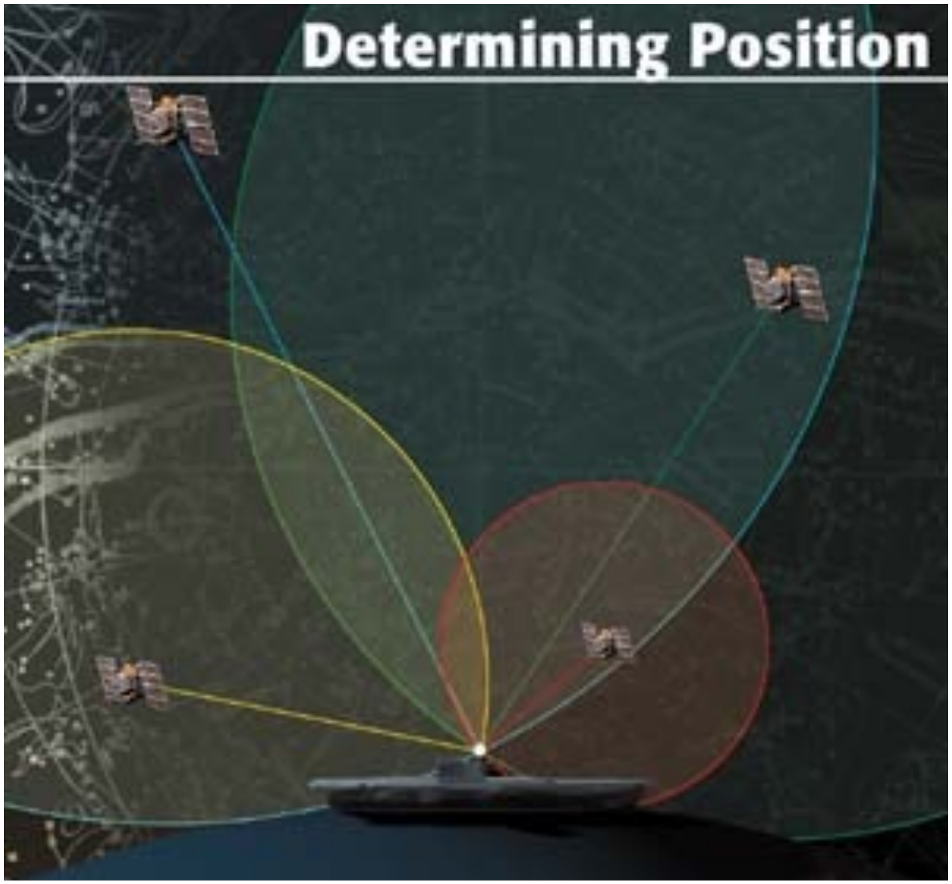
- is always away from the earth's center

On Ellipsoid:

- not the case (except equators & poles)

Trilateration

- GPS receiver measures distances from satellites
- Distance from satellite #1 = 11000 miles
  - We must be on the surface of a sphere of radius 11000 miles, centered at satellite #1
- Distance from satellite #2 = 12000 miles
  - We are also on the surface of a sphere of radius 12000 miles, centered at satellite #2,
- → Point on the circle where the two spheres intersect



Trilateration

- Distance from satellite #3 = 13000 miles
  - We are also on the surface of a sphere of radius 13000 miles, centered at satellite #3
    - i.e., on the two points where this sphere and the circle intersect
    - Usually one of the points is impossible (is not on the Earth) and can be rejected
- Fourth measurement useful for another reason!

Measuring Distances from Satellites

- By timing how long it takes for a signal sent from the satellite to arrive at the receiver
  - We already know the speed of light
- Timing problem is tricky
  - Smallest distance - 0.06 seconds
  - Need some really precise clocks

Measuring Distances from Satellites

- Need some really precise clocks
  - Thousandth of a second error → 200 miles of error
  - On satellite side, atomic clocks provide almost perfectly stable and accurate timing
  - What about on the receiver side?
    - Atomic clocks too expensive!
- Assuming precise clocks, how do we measure travel times?

Measuring Travel Times from Satellites

- Each satellite transmits a unique pseudo-random code, a copy of which is created in real time in the user-set receiver by the internal electronics
- The receiver then gradually time-shifts its internal code until it corresponds to the received code--an event called lock-on.
- Once locked on to a satellite, the receiver can determine the exact timing of the received signal in reference to its own internal clock

What is common…

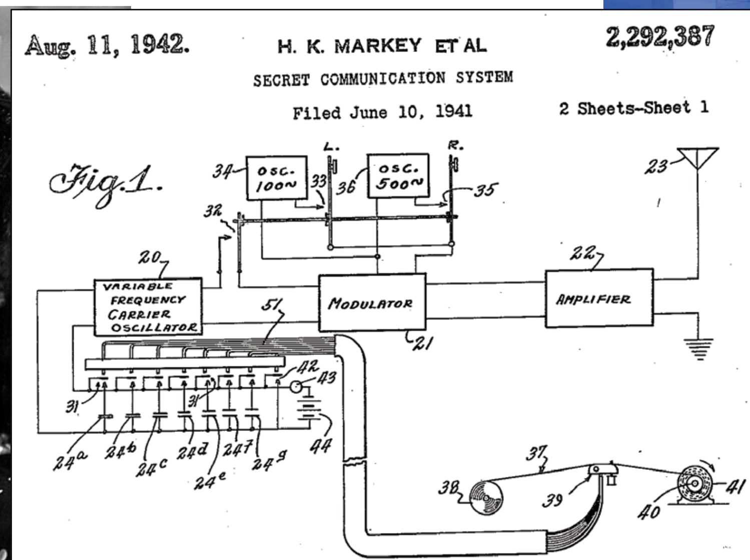
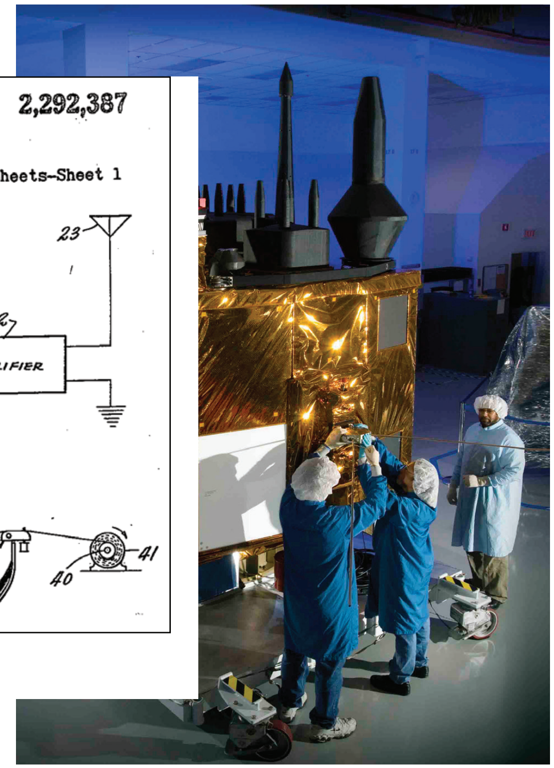
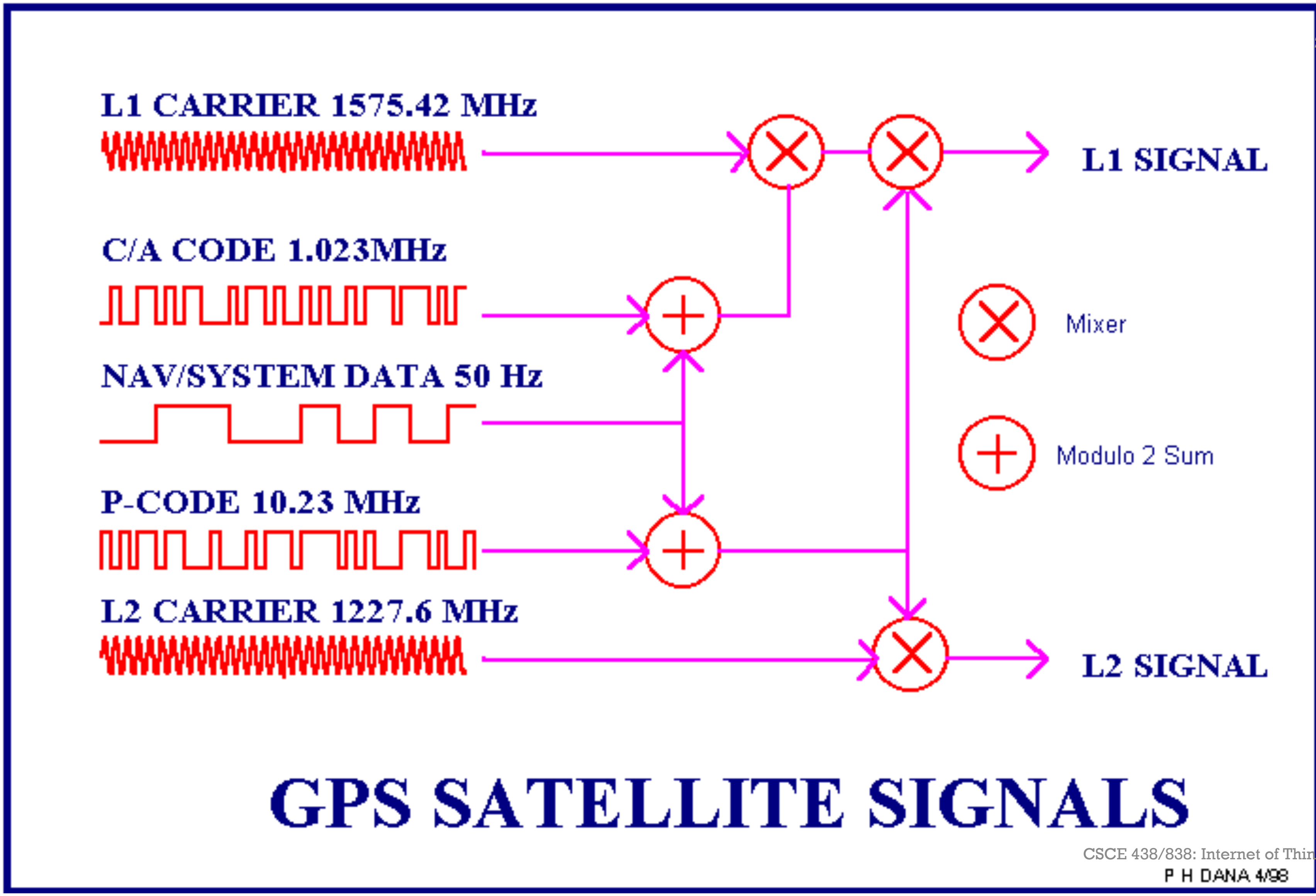


Figure 1 from US Patent 2,292,387

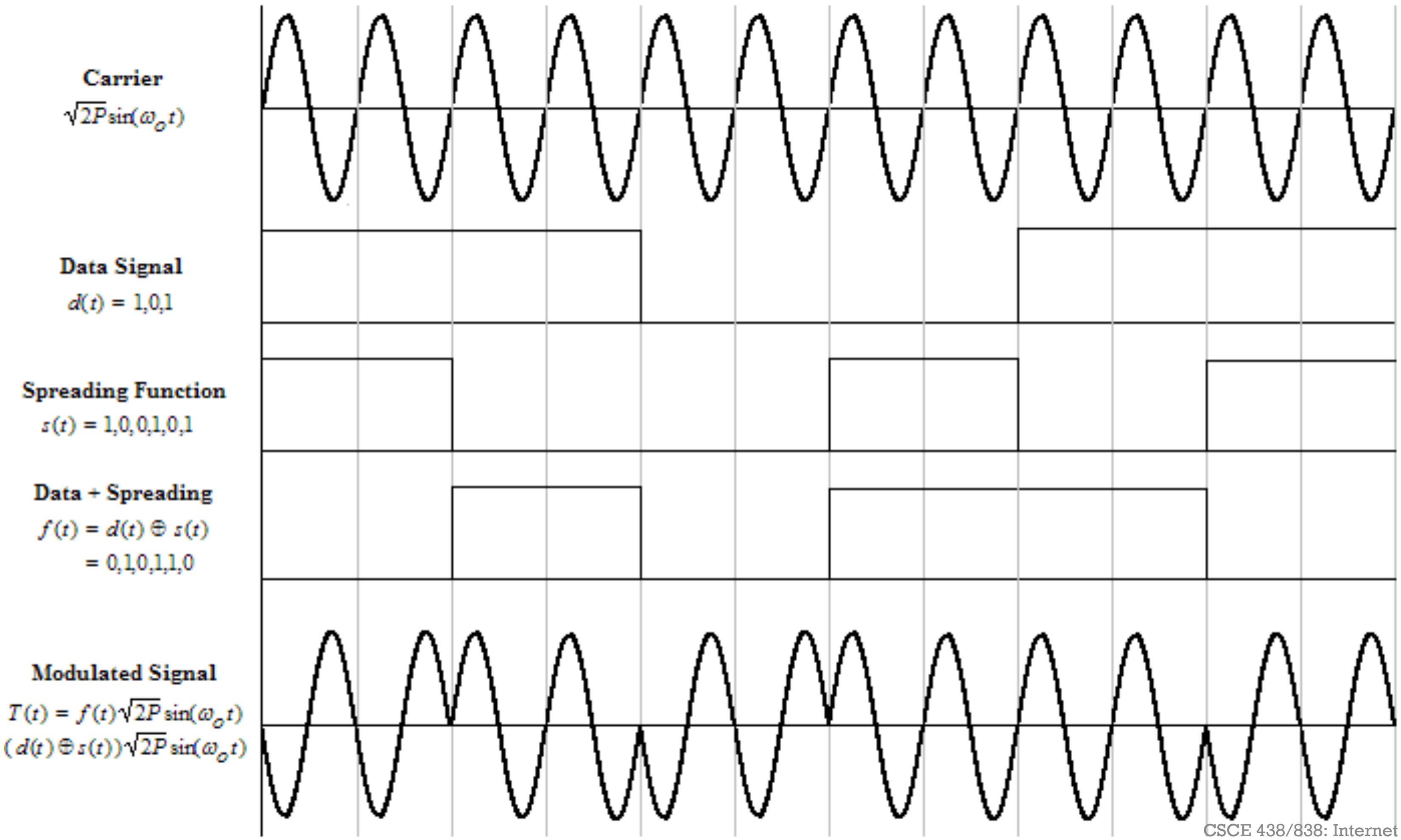


Hedy Lamarr, Hollywood Actress

GPS Satellite


L1 CARRIER 1575.42 MHz
C/A CODE 1.023MHz
NAV/SYSTEM DATA 50 Hz
P-CODE 10.23 MHz
L2 CARRIER 1227.6 MHz
L1 SIGNAL
L2 SIGNAL
Mixer
Modulo 2 Sum
GPS SATELLITE SIGNALS
P H DANA 4/98

BPSK Example



Measuring Travel Times from Satellites

- If receiver clock was perfectly synchronized, three satellites would be enough
- In real GPS receivers, the internal clock is not accurate enough
- The clock bias error can be determined by locking on to four satellites, and solving for X, Y, and Z coordinates, and the clock bias error

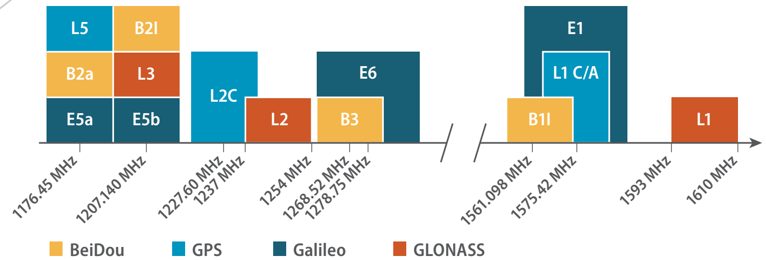
Extra Satellite Measurement to Eliminate Clock Errors

- Three perfect measurements can locate a point in 3D
- Four imperfect measurements can do the same thing
  - If there is error in receiver clock, the fourth measurement will not intersect with the first three
- Receiver looks for a single correction factor

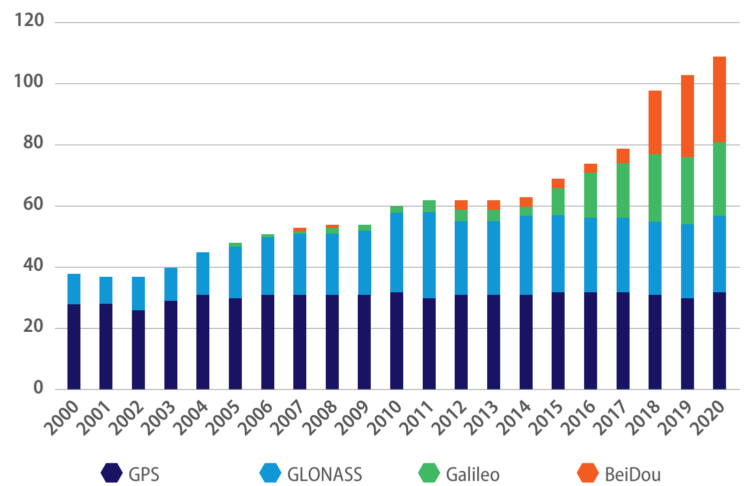
Extra Satellite Measurement to Eliminate Clock Errors

- The correction factor can then be applied to all measurements from then on.
  - From then on its clock is synced to universal time.
  - This correction process would have to be repeated constantly to make sure the receiver's clocks stay synched
- At least four channels are required for four simultaneous measurements

GNSS



- Global Navigation Satellite System
- GPS was the first GNSS



SYSTEM	PROVIDER	SIGNAL
GPS		L1 L1 C L2 L2 C L5
GALILEO		E1 E5 E6
GLONASS		L1 FDMA L1 CDMA L2 FDMA L2 CDMA L3 CDMA L5 CDMA
BEIDOU		B1 B2 B3

European Global Navigation Satellite Systems Agency, GNSS User Technology Report, 2020

Navigation Service

GPS Timekeeping Function

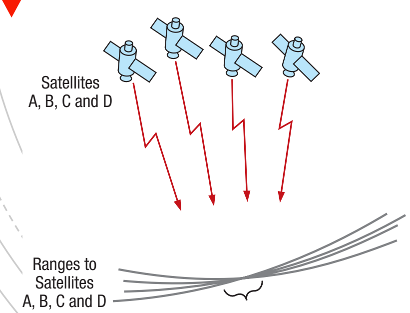
- Navigation Timekeeping:
  - Critical for navigation mission
  - Needed for orbit determination/prediction and internal satellite clock synchronization,
  - Not intended for timing applications
- Metrological Timekeeping:
  - Not critical for navigation
  - Needed to provide a UTC timing services (time dissemination) – governed by US Naval Observatory
  - Supports communication systems, banking, power grid management, etc…

Timing Service

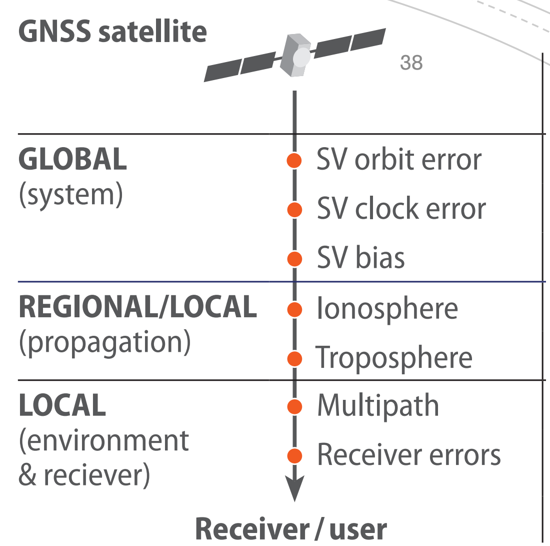
Improving GNSS Accuracy

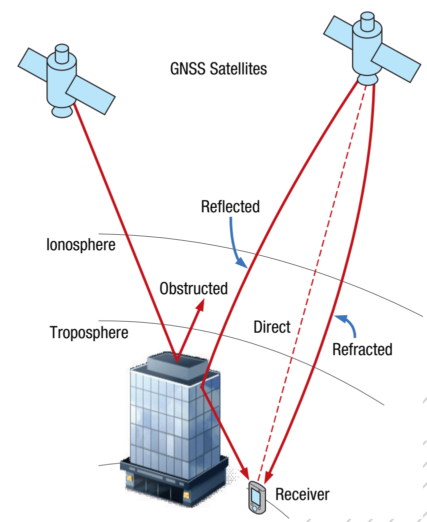
- Sources of error
- DGPS
- RTK
- PPP
- SBAS
- INS
- 5G

Global Positioning System (GPS): Sources of Error



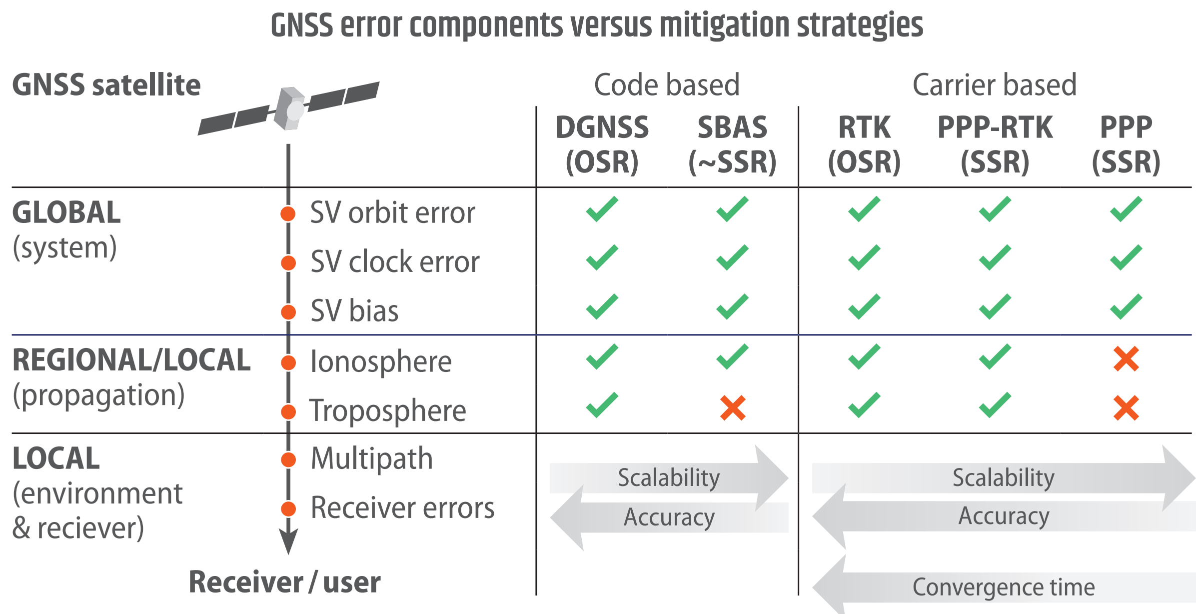
- Ephemeris (satellite) errors
  - Error that effects the satellite's orbit (ephemeris) and satellite clock
  - Caused by the gravitational pull of the sun, moon, and the pressure caused by solar radiation
  - Error monitored by the Department of Defense (DoD) and broadcasted to the GPS satellites
- Environmental errors
  - Speed of light is only a constant in a vacuum
  - Charged Particles in the Ionosphere – frequency-dependent propagation speed
  - Water Molecules in the Troposphere – frequency-independent delays
- Local errors
  - Timing error from signals bouncing off of objects such as buildings or mountains
  - Satellite geometry
  - Quality of receiver (clock stability, processing noise, hardware biases)
  - Antenna quality





European Global Navigation Satellite Systems Agency, GNSS User Technology Report, 2020
NovAtel Inc., An Introduction to GNSS, 2nd edition

Error Mitigation Strategies



GPS Error Budget

- Atmospheric Delays
  - Ionosphere Errors
    - Single Frequency L1 only error (± 5m)
    - (L1 and L2) Dual Frequency GPS (<< 1m)
  - Troposphere Errors (± 0.5m)
- Ephemeris/Orbit Error (± 2.5m)
- Clock Error (± 2m)
- Multipath (± 1m)
- Receiver Error (± 0.3m)
- How can we reduce errors caused by the atmosphere?

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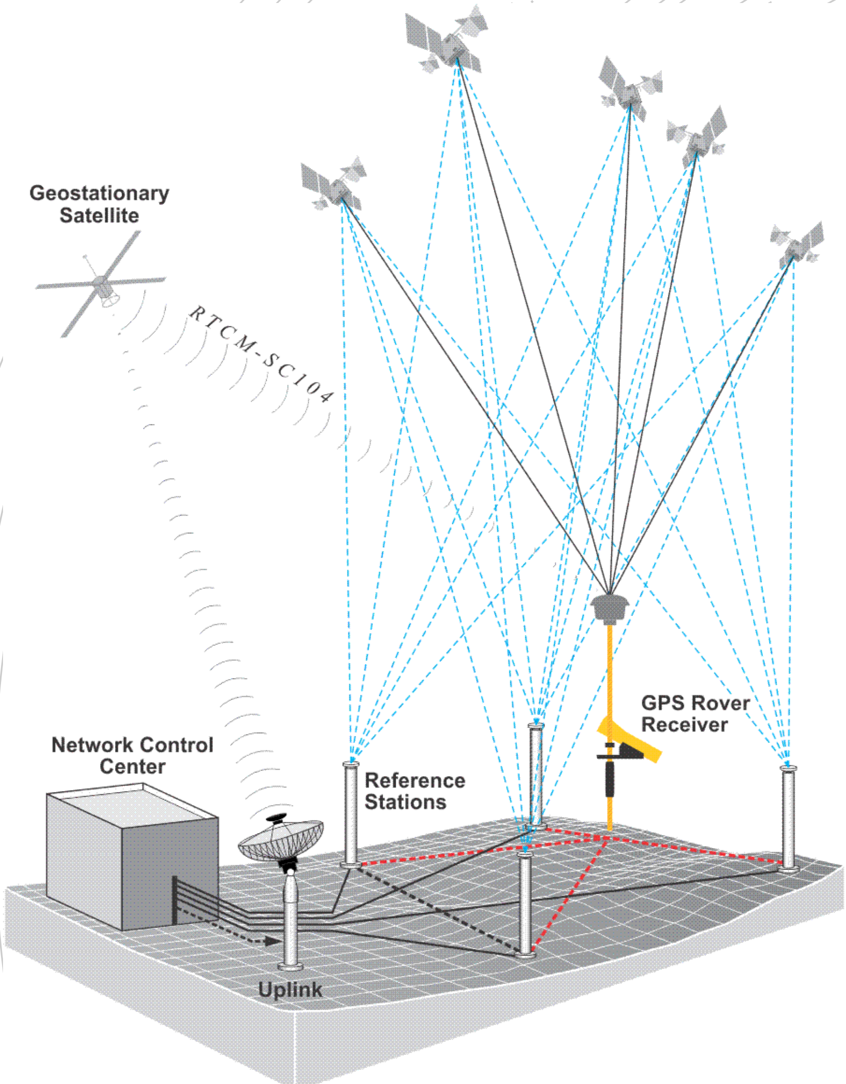
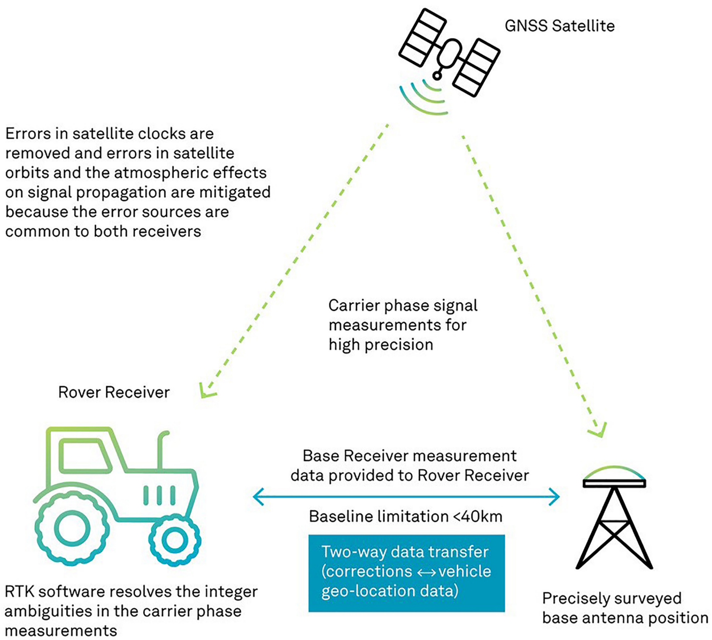
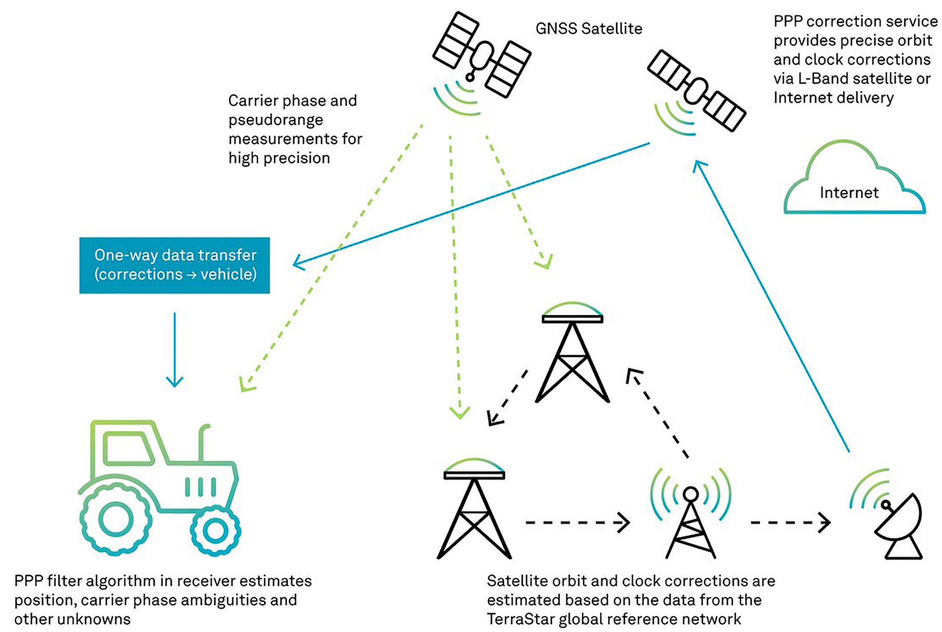


- DGPS = Differential GPS
- Basic Idea:
  - Use known locations on Earth as reference locations
    - Exact Position is known, compare to the location determined by GPS
    - Develop error correction data by using the difference of the exact location and the GPS determined location
  - Broadcast error correction data to local GPS receivers (receivers within 200km of the reference station)
  - Error correction can remove errors caused by the atmosphere—makes GPS data more accurate!
- Nationwide DGPS (NDPGS)
  - Initiated by U.S. and Canadian Coastal Guards
- Now global – evolved into real-time kinematic (RTK)

RTK vs PPP



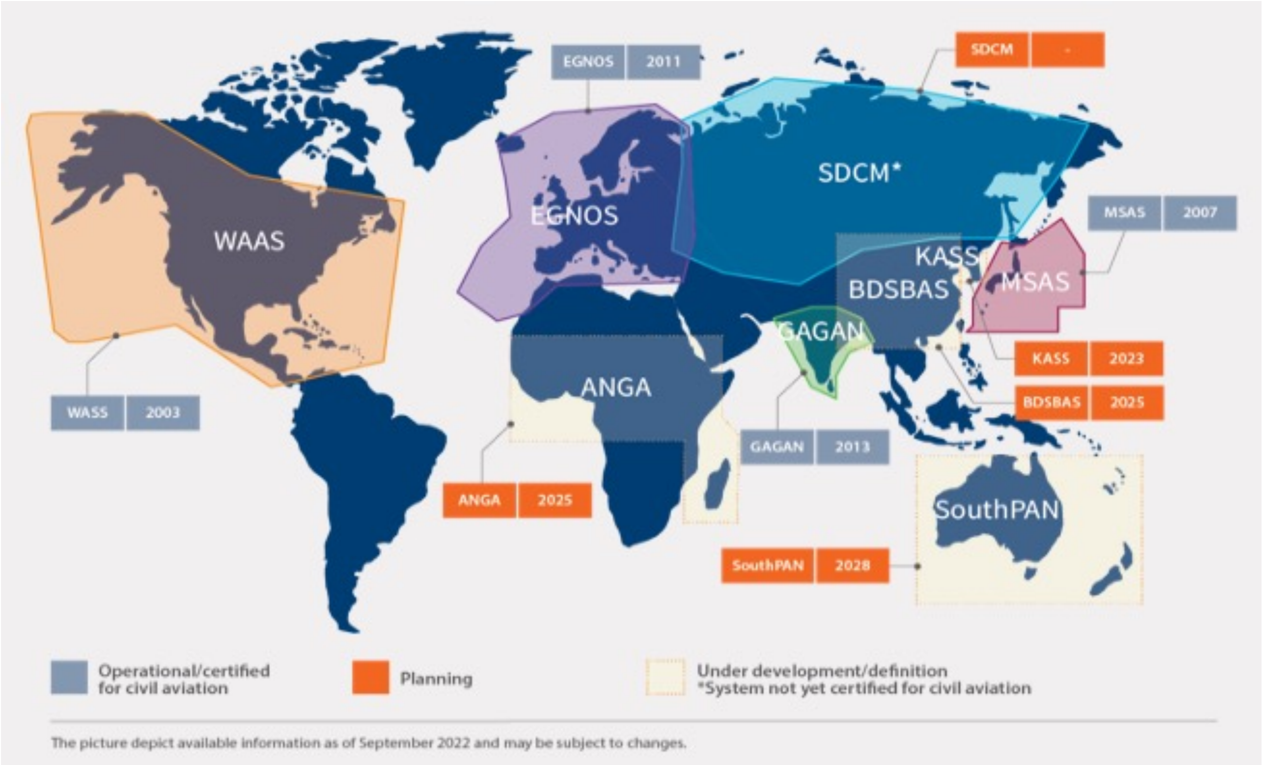
RTK



Precise Point Positioning

Hexagon, White paper, Global Breakthrough in PPP Technology: “RTK From the Sky”

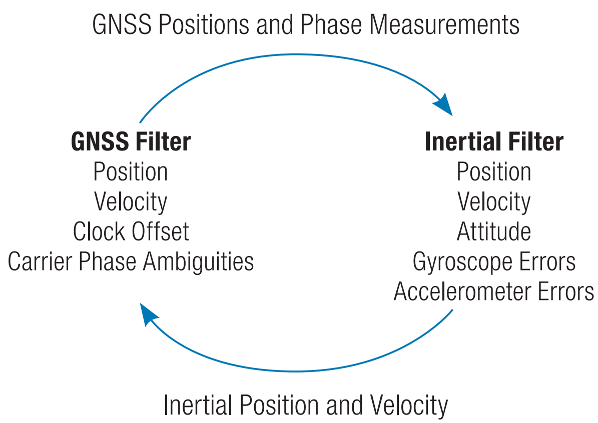
Satellite Based Augmentation Systems (SBAS)



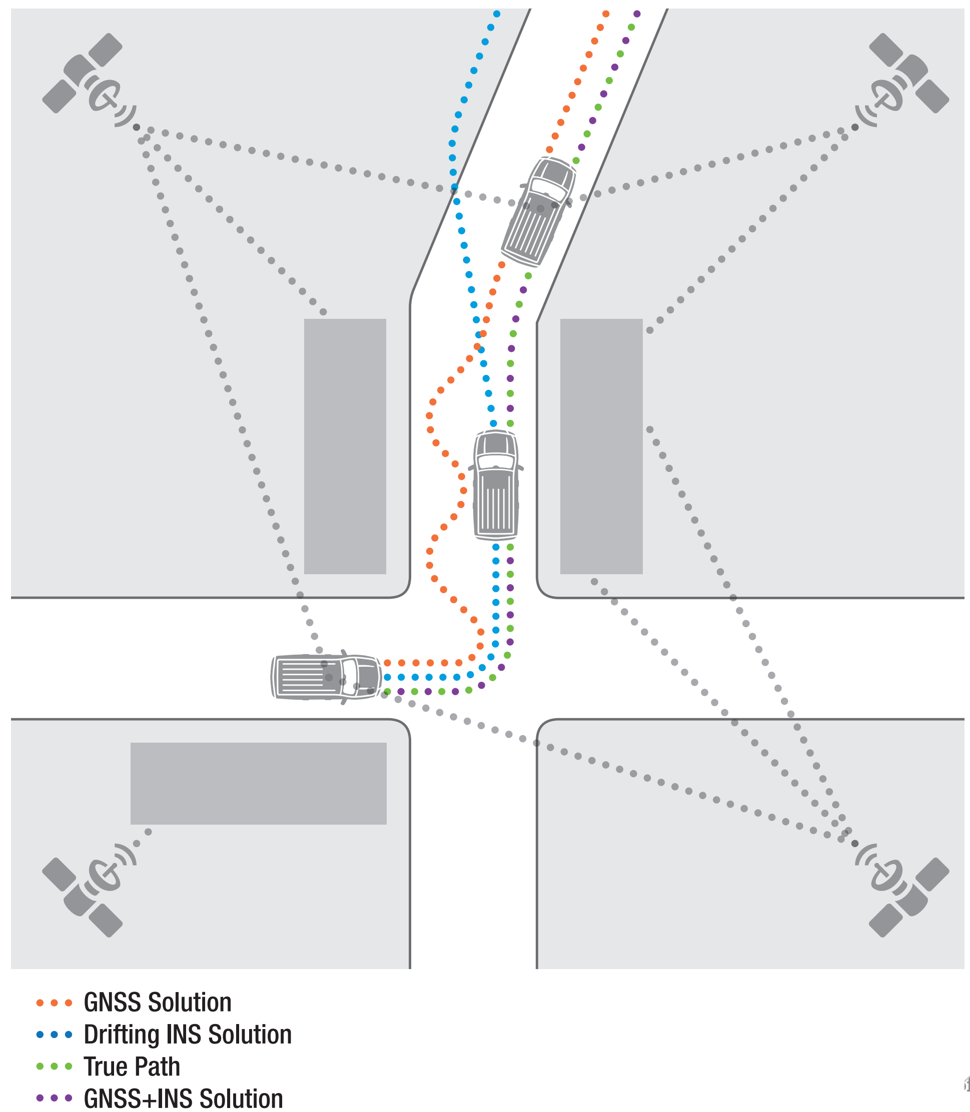
European Global Navigation Satellite Systems Agency, GNSS User Technology Report, 2020

GNSS + INS

- Inertial navigation systems (INS) can be used to augment position accuracy in denied areas
- Inertial measurement units (IMU) can measure precise relative 3D movement
- INS can use this information to calculate position and velocity
- Sensor fusion – use any sensor available
  - Odometer
  - Vision-aided navigation



GNSS + INS


GNSS Solution
Drifting INS Solution
True Path
GNSS+INS Solution

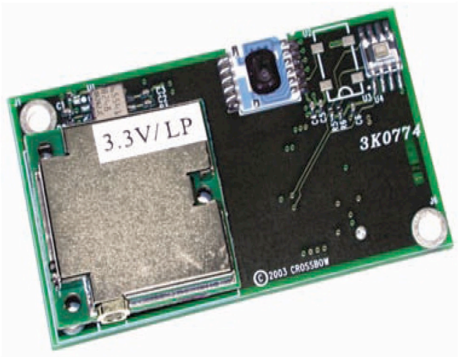
Hybrid GNSS/5G

- <5G: Positioning has been an afterthought
- 5G
  - Wide bandwidth – better time resolution
  - mmWave – better time of arrival (ToA) estimation
  - Massive antenna arrays – better direction of arrival (DoA) estimation
- 5G will augment GNSS in deep urban environments where GNSS reception is poor
- Massive IoT – ports, airports, railways, roads
- Mission critical services – vehicle-to-X, intelligent transport systems, autonomous vehicles, Industry 4.0 automation

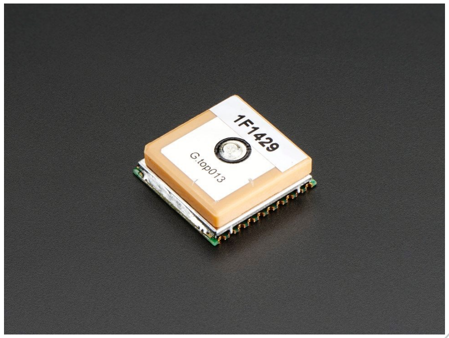
Questions?

GPS in IoT

- Xbow MTS420CA: Environmental monitoring sensor board
- For Mica2 and MicaZ
- Tracking channels: 12
- Position accuracy: 10 m



- Adafruit MTK3339
- Tracking channels: 66 (up to 22 satellites)
- Position accuracy: 3 m



GPS in IoT

- GPS does NOT work indoors
- It might be expensive for the budget
- GPS-less techniques are required

Localization Algorithms

- Range-Based Localization
- Range-Free Localization

Range-based Localization

- REQUIREMENT: Beacon devices with accurate location information must exist
- Using several ranging techniques (EXPLAINED LATER) the remaining nodes in the network estimate their distance to three or more beacon nodes
- Using this information, the location of a node is estimated.

Range-free Localization

- Do not require distance estimation
- The existence of a beacon device may still be required,
- The location of other nodes is estimated through range-free techniques

Ranging Techniques

- Received Signal Strength (RSS)
- Time of Arrival (TOA)
- Time Difference of Arrival (TDOA)
- Angle of Arrival (AOA)

Received Signal Strength (RSS)

- BASIC IDEA:
- The following information is used to estimate the distance of a transmitter to a receiver:

- a. The Power of the Received Signal
- b. Knowledge of Transmitter Power
- c. Path Loss Model

Received Signal Strength (RSS)

- Each measurement gives a circle on which the sensor must lie
- RSS method may be unreliable and inaccurate due to:
- a. Multi-path effects
- b. Shadowing, scattering, and other impairments
- c. Non line-of-sight conditions

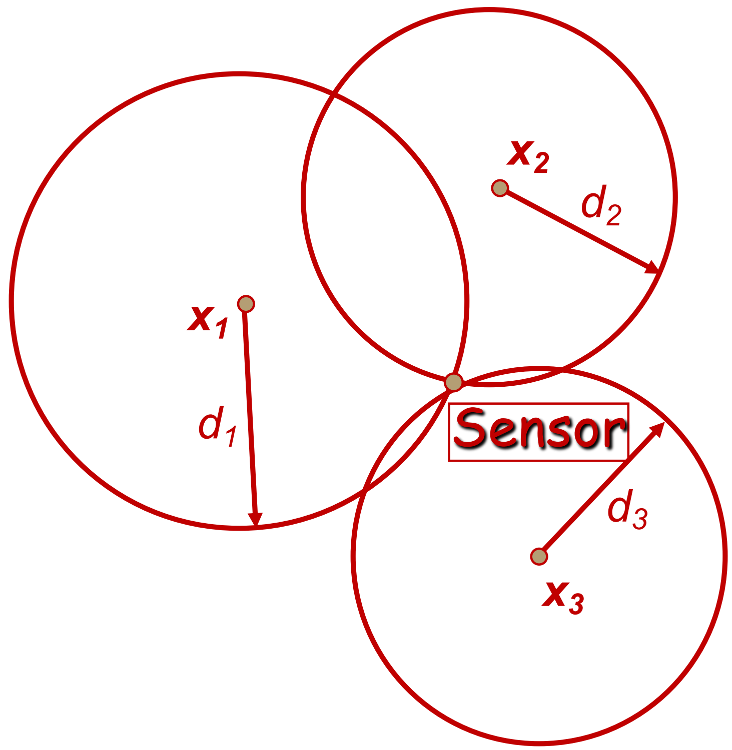
Time of Arrival (ToA)

- BASIC IDEA:
  - Estimate the relative distance to a beacon by applying the measured propagation time to a complex distance formula.

Time of Arrival (ToA)

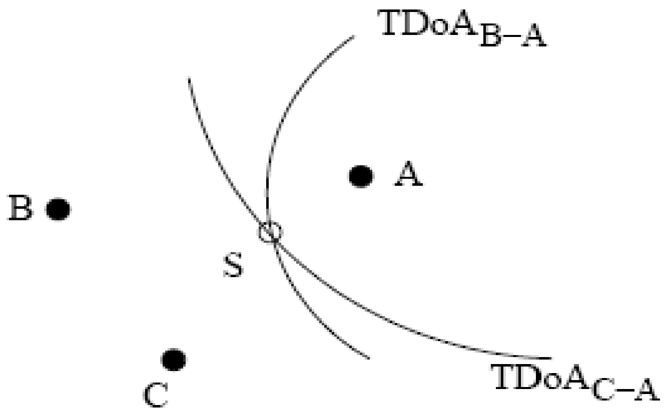
- Active: Receiver sends a signal that is bounced back so that the receiver know the round-trip time
  - IR ranging
- Passive: Receiver and transmitter are separate
- Time of signal transmission needs to be known
- A drawback is due to fast propagation speed of wireless signals where a small error in time measurement can result in large distance estimate errors

Localization via RSSI or ToA



Time Difference of Arrival (TDoA)

- BASIC IDEA:
- Time of signal transmission need not to be known
- Each TDoA measurement defines line-of-position as a hyperbola
- Location of sensor is at the intersection of the hyperbolas



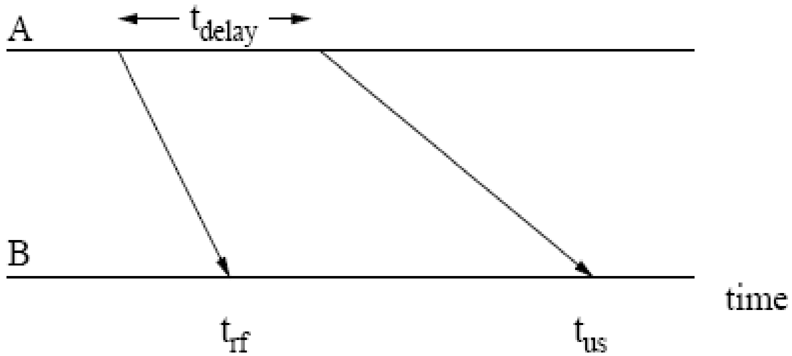
Localization via Multi-node TDoA

- Three beacons are used to accurately locate a node using TDoA measurements
- The node to be localized, i.e., S, measures the arrival time of beacons sent from A, B, and C
- Assumptions:
  - Three nodes are synchronized
  - They transmit the beacon signals at the same time
- The difference between the received times of a pair of beacon nodes define a hyperbola on which the node S should reside.
- The intersection of the two hyperbolas is then used to locate the node S.

Multisignal TDoA

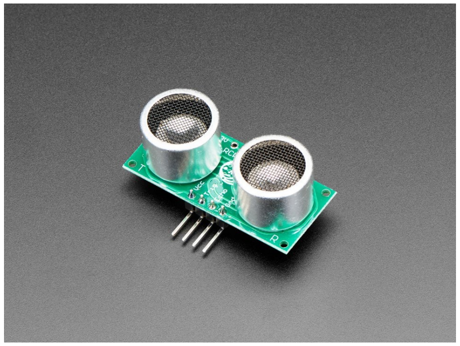
- Instead, two different types of signals can be used by a node to estimate its distance to another node.

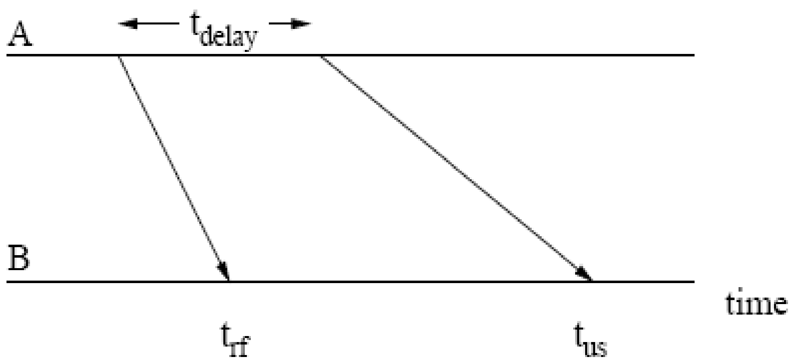
- By using two signals that have different propagation speeds, the time difference of arrival of these signals can be used to estimate the distance



Example: Multisignal TDoA

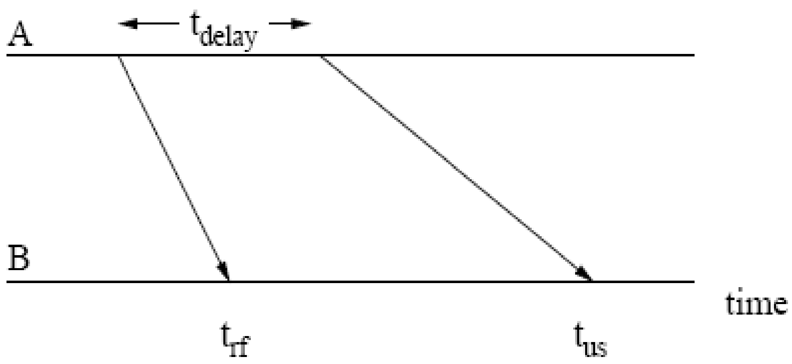
- Node A transmits two signals and node B, which estimates the distance to node A based on the difference in time of arrival of the two signals.
- A common approach for the multisignal TDoA is to use an RF signal in conjunction with an ultrasound microphone and speaker





Example: Multisignal TDoA

- Node A, first transmits an RF signal, which is received by the node B at time t_{rf}
- Node A, then waits for a time t_{delay}, which is also known by node B and transmits an ultrasound signal.
- This signal is received by node B at time t_{us}.



Example: Multisignal TDoA

- The distance between the two nodes:
- $$d_{AB} = (s_{rf}-s_{us})(t_{us}-t_{delay}-t_{rf})$$
- s_{rf} is the speed of RF waves and s_{us} is the speed of ultrasound.
- RF waves travel significantly faster than ultrasound waves
- The difference between the receive times of these two signals can be used to accurately measure the distance
- Localization accuracy up to centimeters is possible.

Evaluation of TDoA

- Multisignal TDoA technique provides high accuracy under line-of-sight conditions

- However, similar to the RSS based techniques, non-line-of-sight communication may lead to high localization errors.

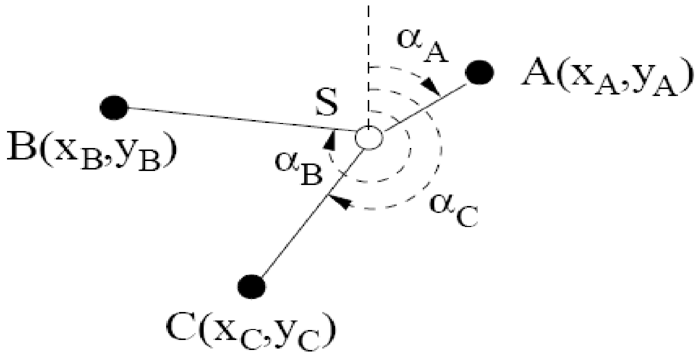
- Because of the different paths either type of signal may follow, Non-line-of-sight communication leads to significantly different propagation delays.

Evaluation of TDoA

- Need to consider the NLOS communication case to improve the accuracy.
- Compared to RSS based localization, TDoA techniques require additional transmitter receiver pairs in each node for the second type of signal.
- May not be suitable for some applications.

Angle of Arrival (AoA)

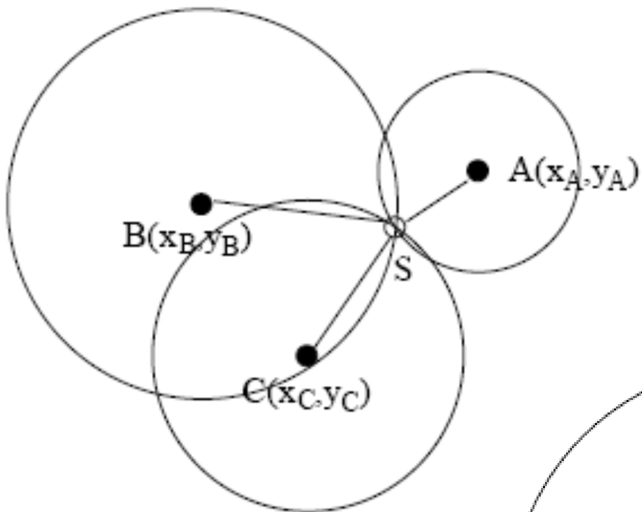
- Special antenna configurations are used to estimate the angle of arrival of the received signal from a beacon node
- Angle of arrival method may also be unreliable and inaccurate due to:
- a. Multi-path effects,
- b. Shadowing, scattering, and other impairments,
- c. Non line of sight conditions.



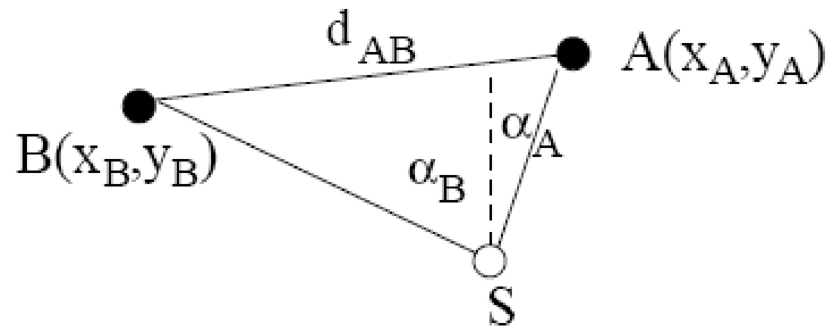
Localization via AoA

- A node S with unknown location, (x_S,y_S) receives beacon signals from nodes A, B, and C with well known locations, (x_A, y_A), (x_B, y_B), and (x_C, y_C), respectively.
- Then, node S estimates the AoA of each beacon, i.e., a_A, a_B, and a_C.
- AoA measurements are then combined with their locations to estimate the location of the node S through.

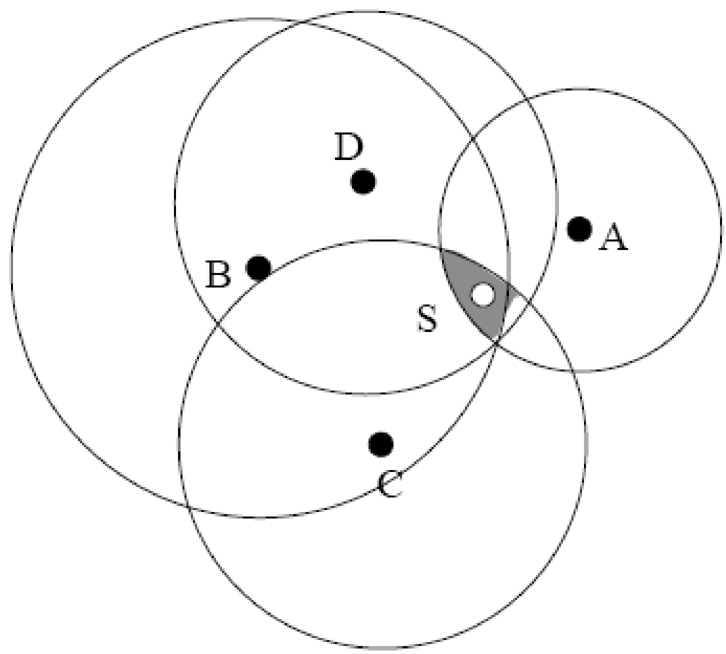
- Three main localization techniques



(a) Trilateration.

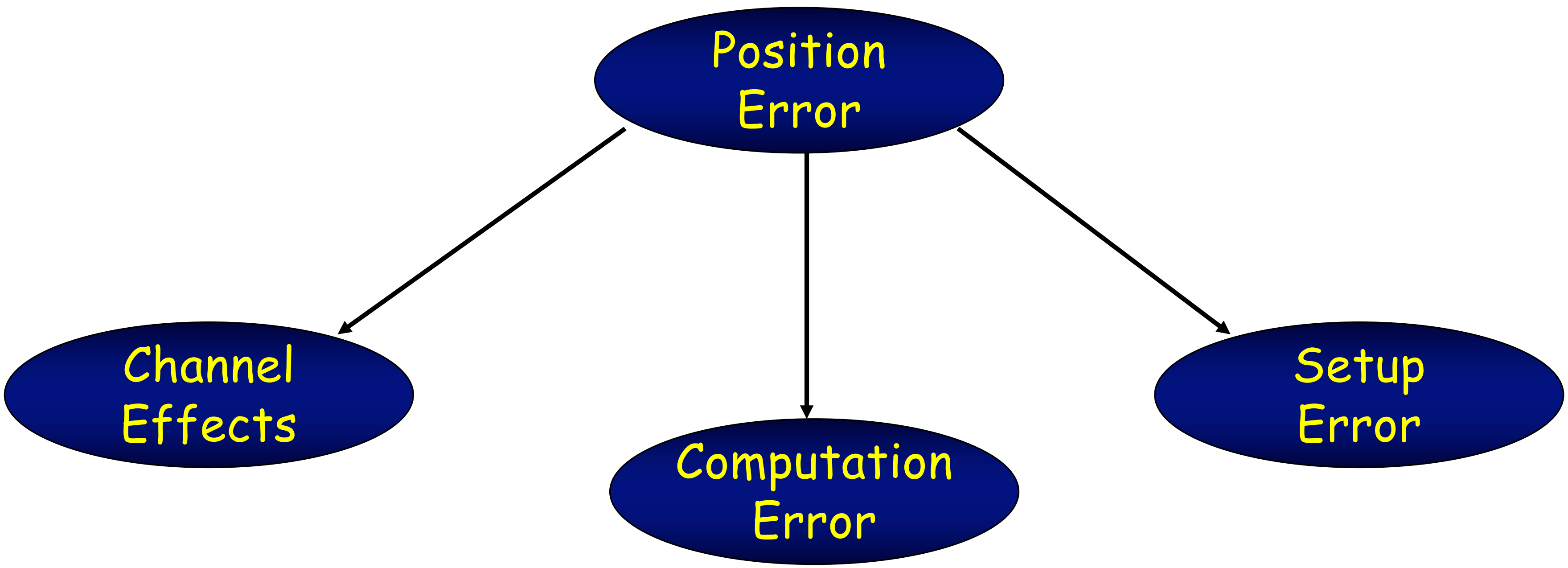


(b) Triangulation.



(c) Multilateration.

Estimated Location Error Decomposition



Sources of Errors

- Multipath
  - RSSI
    - Up to 30-40 dB variation
    - May be combated by using pre-measured signal strength contours

Sources of Errors

- AoA
  - Scattering near and around the sensor & beacon affects the measured AoA
  - At short distances, signals arrive with a large AoA spread, and therefore AoA may be impractical

Sources of Errors

- ToA and TDoA
  - Influenced by the presence of multipath fading
    - Results in a shift in the peak of the correlation

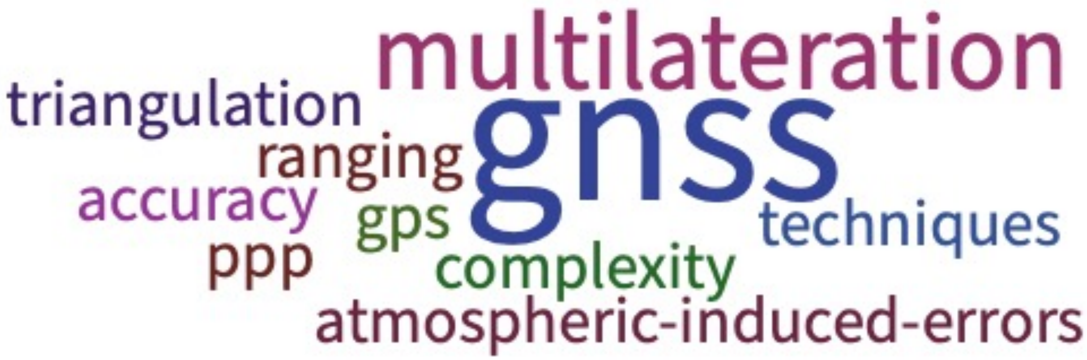
Sources of Errors

- Non line-of-sight (NLoS)
  - AoA
    - Signal arrives at a different angle
    - Can be disaster for AoA if received AoA much different from true AoA
  - ToA/TDoA
    - The measured distance may be considerably greater than true distances

OVERALL OPEN RESEARCH ISSUES

- Localization is domain specific
- Still many open problems
- Design decisions based on availability of technology, and constraints of the operating environment
  - Can we have powerful computation?
  - What is the availability of infrastructure support?
  - What type of obstructions are in the environment?
  - How fast, accurate, reliable should the localization process be?
  - Role of AI in localization?

Which concept was the most intriguing? (one word)



Total Results: 0