SCHULICH SCHOOL OF ENGINEERING

An Introduction to Wireless Location

for Calgary Unix Users Group

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Agenda

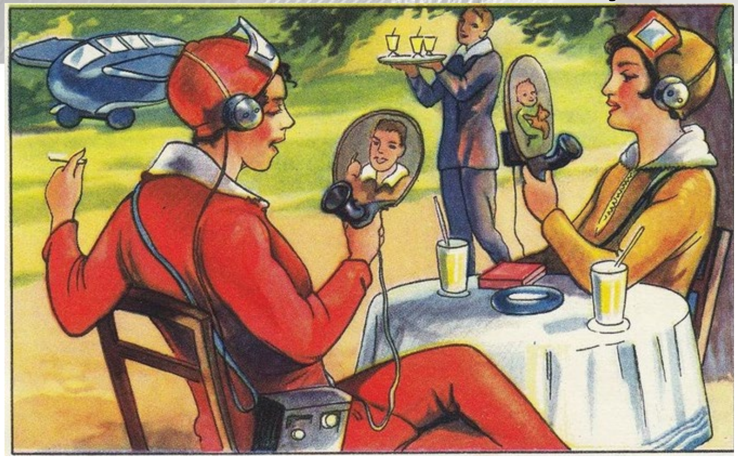
1. Introductory Geomatics Stuff
   a. Basics: History, Coordinates, Angles, Maps
   b. Measurements/Methods/Models
   c. Accuracy vs. Precision
2. Wireless Location Methods
   a. Phones
   b. Bearing Distance, Bearing Power, Cell ID
   c. GPS, WiFi, cellular fingerprinting, BlueTooth

Introduction to Wireless Location

- Wireless Location
  - Locating devices using radio (wireless) signals
- Position, Location, Navigation?
  - In other languages (eg. French) this matters:
    - Locate is to find, Position is to place, Navigate is to move from your current location to a new position
- Formerly called radio-navigation
  - Ships, planes, spacecraft
    - Specialized electronics on board: radios, sensors, computers
- Now everyone has "electronics on board"
    - Smart phones include radios, sensors and a computer
- Location is important
  - Safety: Enhanced 911
  - Convenience: Turn-by-turn directions
  - Location-based Services: E-commerce wants to know where you shop
  - Fun: Pokémon Go

Introduction - History

- Radio-navigation since mid-1920s
- Cell phones since 1947
  - 1982 1G in US, 1991 2G in Finland, 3G 2007
- GPS in development since 1978
  - Fully operational 1995
  - Selective Availability turned off 2000
    - Civilians went from 70 m to 5 m accuracy
- WiFi 1999
- E911 deadline 2001
  - But GPS on phones not really common until 2007
  - Phone companies came up with network-based tracking methods

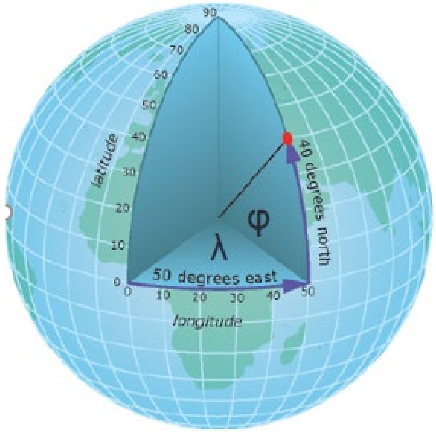


“Vision of the Future” Echte Wagner (1930) “Wireless Private Phone and Television. Everyone now has their own transmitter and receiver and can communicate with friends and relatives. But the television technology has also improved so much that people can speak to each other in real time. Transmitters and receivers are no longer bound to their location, but are always placed in a box of the size of a camera.”

Introduction – Some Basics

- We want to solve for our location
  - 2 or 3 coordinates
- We have observations
  - Distances, angles, signal strengths
- We have models to relate observations to coordinates
- An algebra problem: 2+ equations in 2+ unknowns

- Geographic Coordinates:
  - latitude, longitude, height (φ, λ, h)
  - on the globe
  - curvilinear
- Map Coordinates
  - North, East, Up (or E,N,U)
  - On a map projection
  - Rectilinear
  - Local, or not, eg. ENU, xyz,…
  - Lots of different map systems



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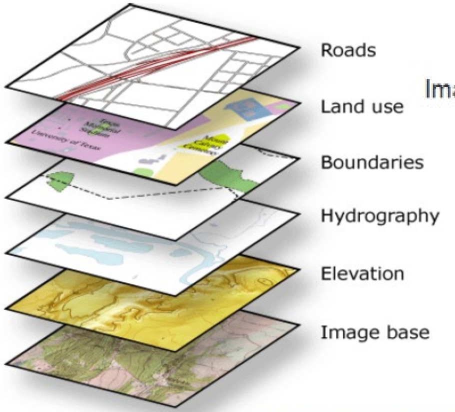
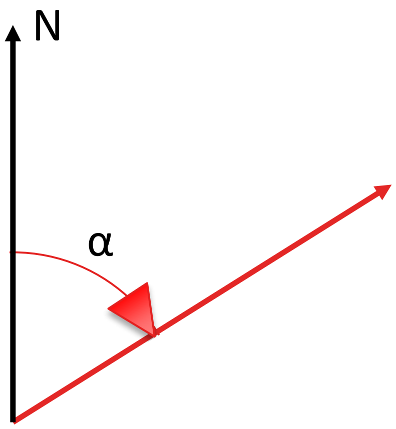


Image source: desktop.arcgis.com/

Azimuth vs Bearing

- Azimuth
  - Clockwise positive angle from North
- Bearing
  - A angle with respect to some direction
- Which North?
  - Geographic
    - All north-south range roads in Alberta geo-north
  - Grid
    - Map projection North, depends on th (eg UTM)
  - Magnetic
    - Points North-east in Alberta but is changing



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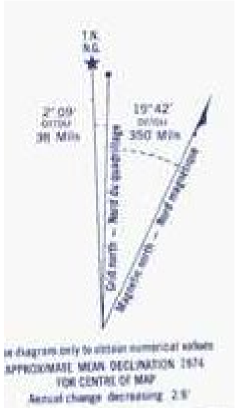
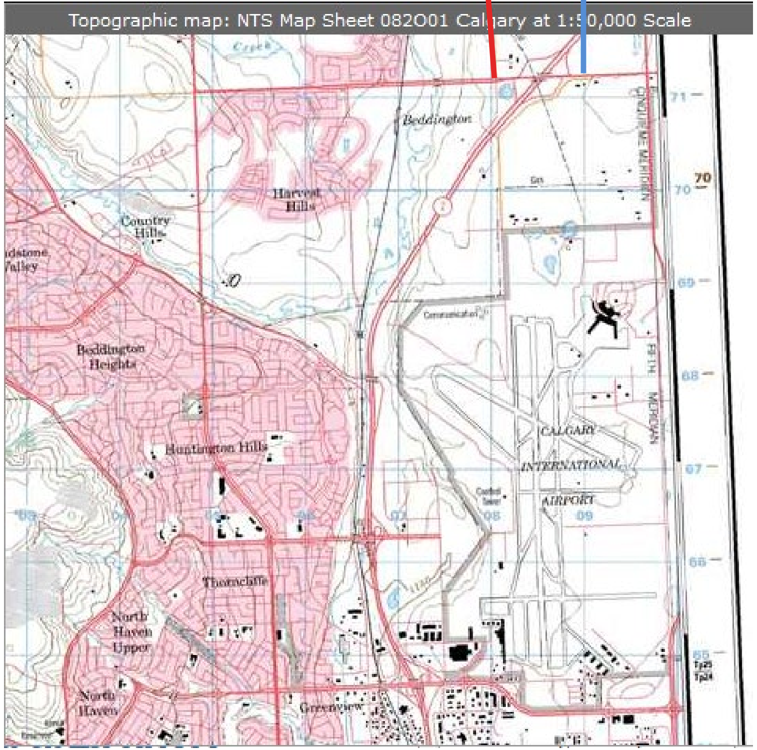
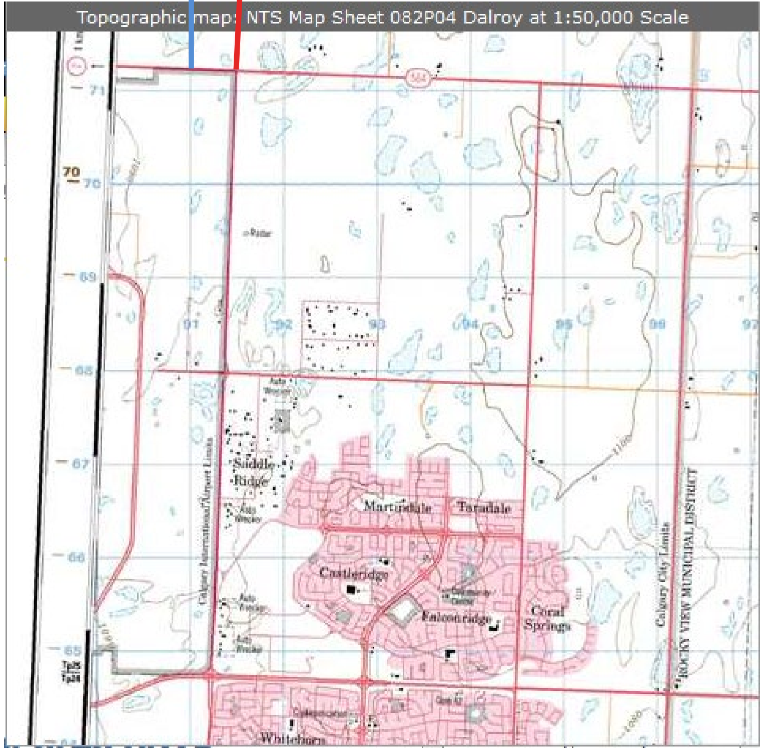
Grid North vs Geographic North



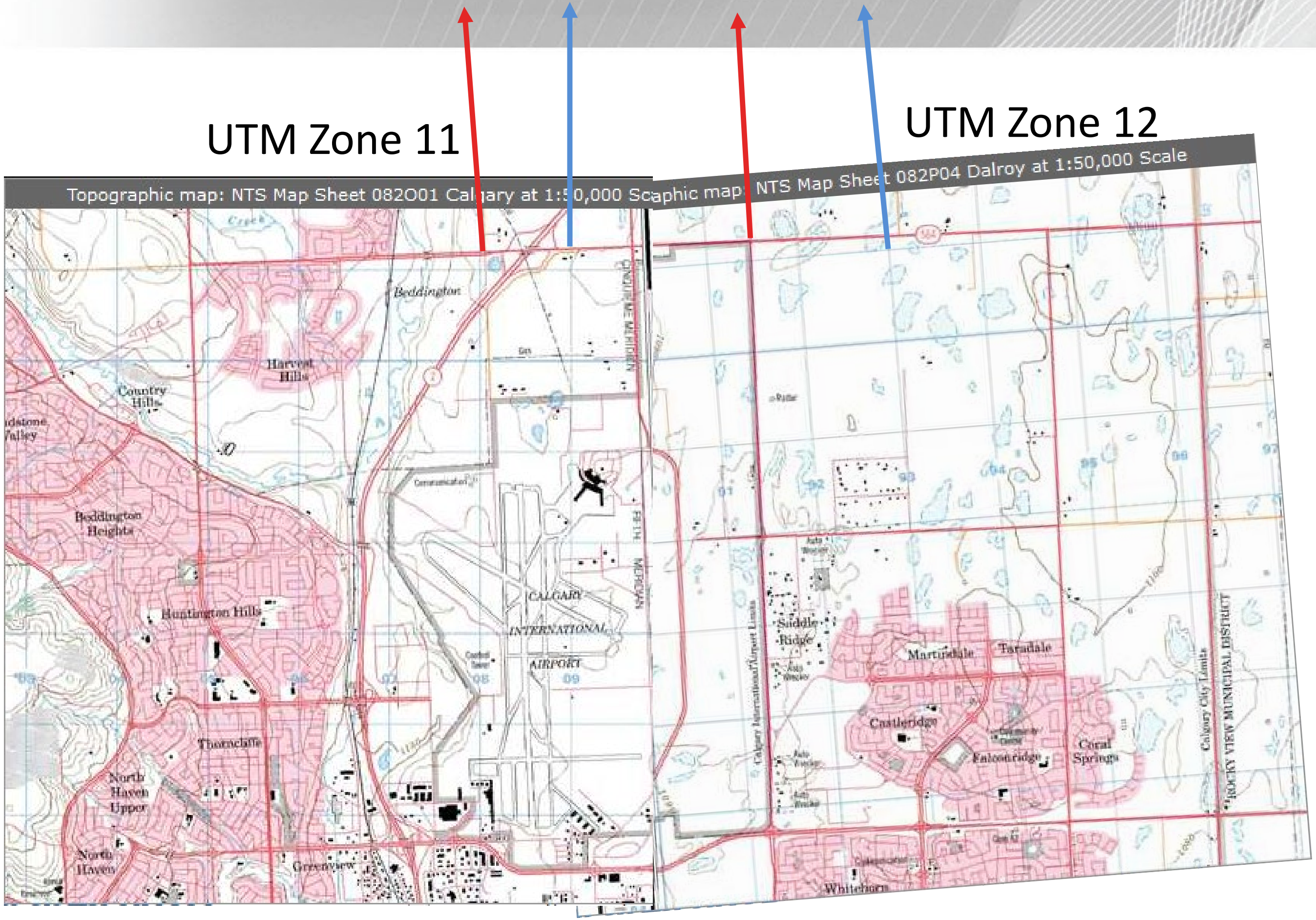
UTM Zone 11



UTM Zone 12

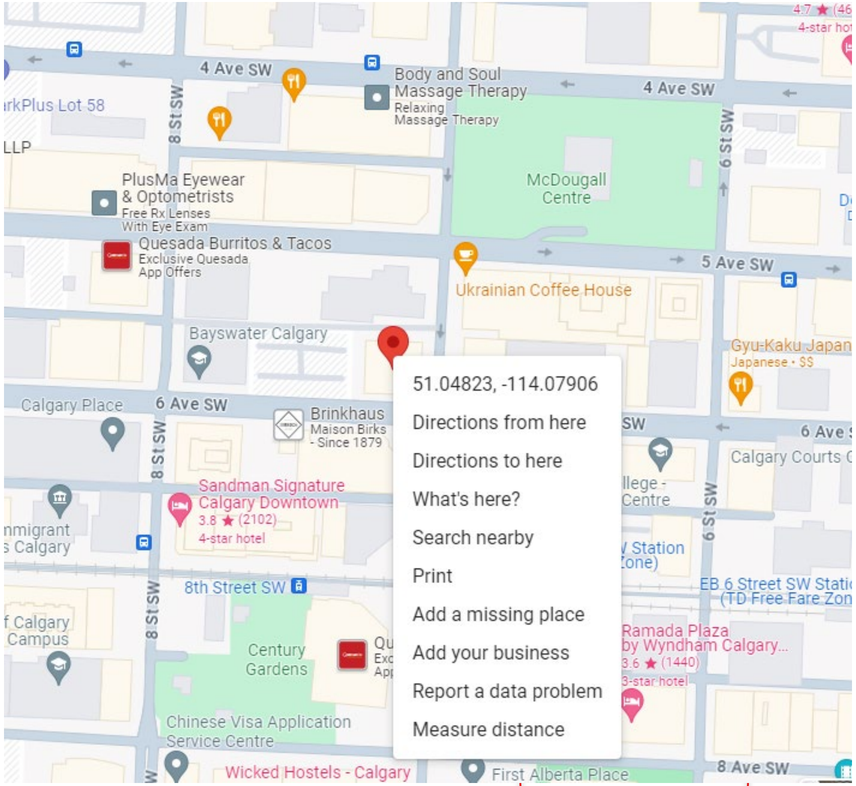


Grid North vs Geographic North



Why use map coordinates?

- Online tools mostly use geographic North
- Google displays lat/long
- Difficult to visualize scale in degrees
  - 1 degree N ≈ 111 km
  - 1 degree E ≈ 70 km (at 51 N)
  - 1/60 degree N = 1 nautical mile



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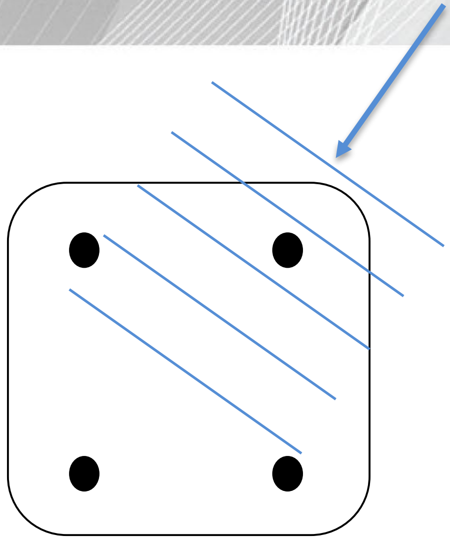
Measurements

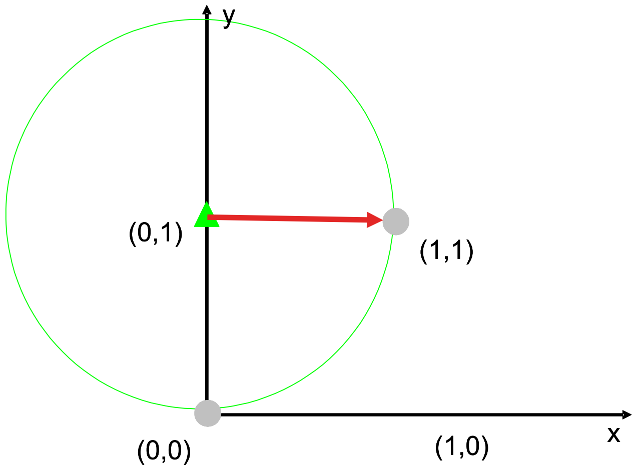
- Angles
  - Directional Antennas
    - Dishes, Yaggi, Arrays (eg. 1980s LoJack)
  - Coded circles (surveying instruments)
- Distances
  - 2 way time of flight (laser or radio)
- Pseudoranges
  - One-way time of flight (GPS)



Members of the Calgary police collision reconstruction unit collect evidence at the scene of a serious pedestrian collision in Mission on Tuesday, April 11 2017. Ryan McLeod/Postmedia Network

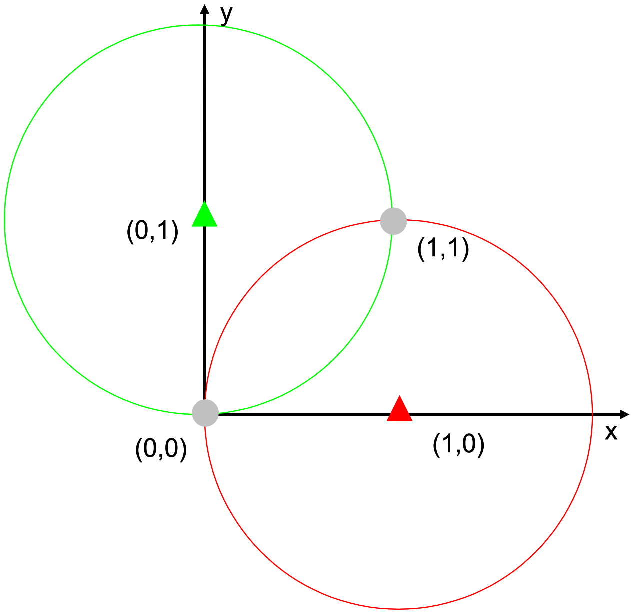
- Angle-Distance

  (aka Range-Bearing)



- Distance-Distance

  (aka Range-Range)

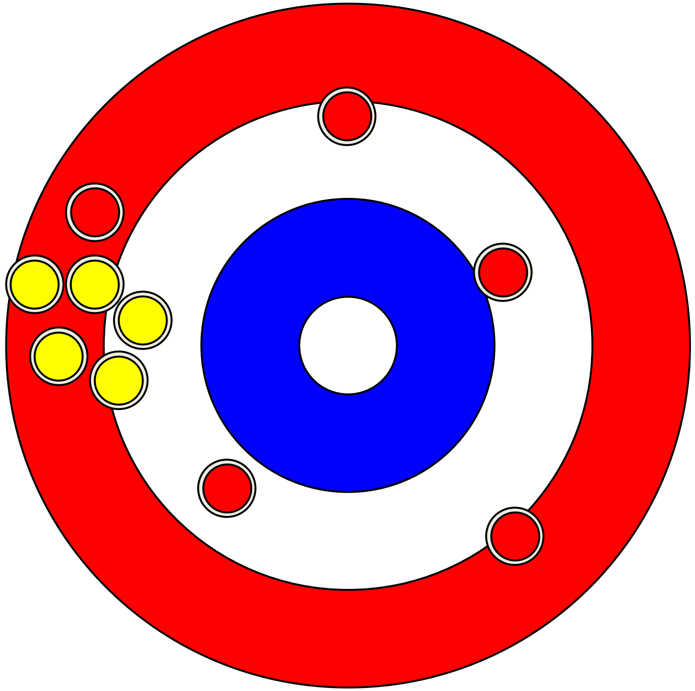


Accuracy and Precision

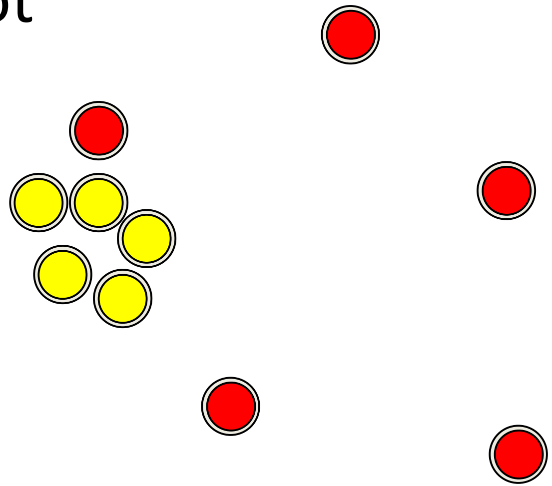
- Accuracy
  - Closeness to the truth, is the average close?
- Precision
  - Repeatability or "standard deviation"
- $\text{Error}^2 = \text{bias}^2 + \text{standard deviation}^2$

$$\text{RMS} = \sqrt{mean^2 + \sigma^2}$$

- When the true solution is known, accuracy can be assessed from a sample:
  - Yellow:
    - Precise: Yes
    - Accurate: No
  - Red:
    - Precise: No
    - Accurate: Yes



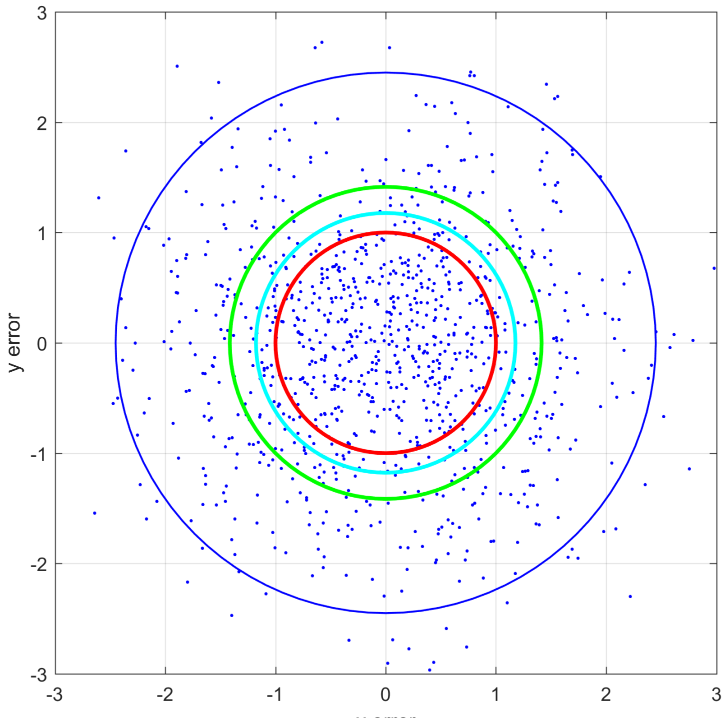
- When the true solution is not known, accuracy can not be assessed :
  - Yellow:
    - Precise: Yes
    - Accurate: ??
  - Red:
    - Precise: No
    - Accurate: ??



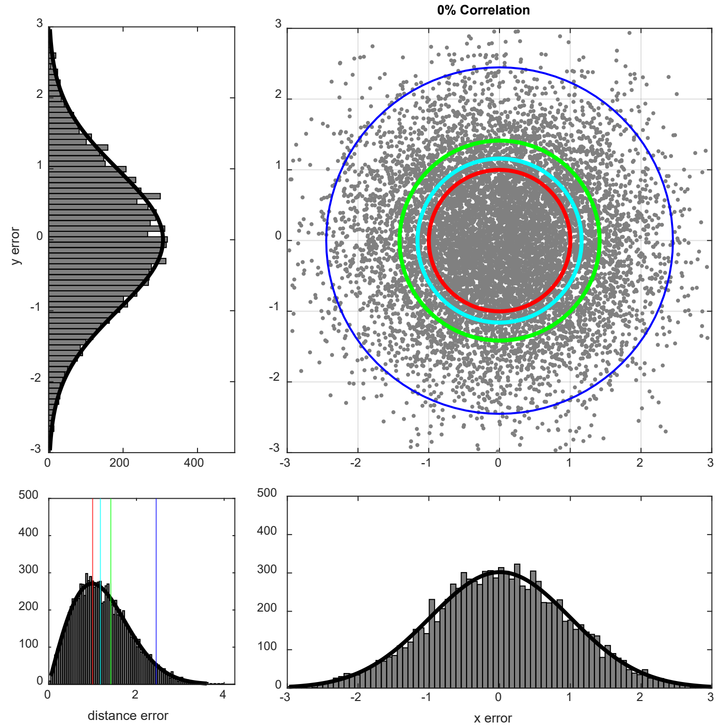
Accuracy Measures

Accuracy Measures derived from the Error Covariance Matrix $C_{\hat{x}}$

- Error Ellipse
  - From eigenvalues and vectors of $C_{\hat{x}}$
- 95% confidence region (2.45 x error ellipse)
- "RMS circle"
  - RMS = $\sqrt{mean^2 + \sigma^2}$
  - Valid if mean error = 0
  - RMS = $\sqrt{\sigma_x^2 + \sigma_y^2}$
  - aka *DRMS*
- Circular Error Probable (median 2D error)

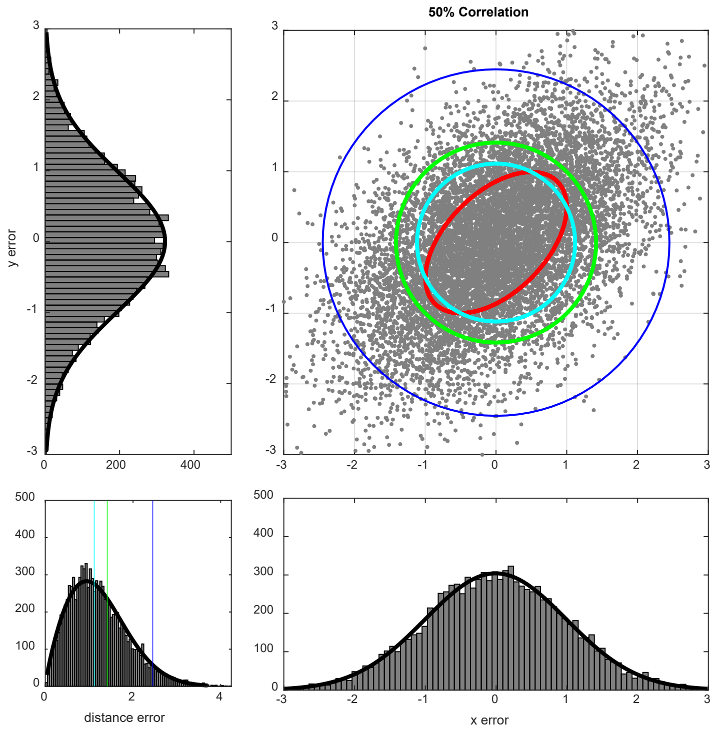


- What about when $C_{\hat{x}}$ is not diagonal?
  - x and y distributions remain the same
  - But they become less independent
  - Error Ellipse 39%
  - CEP = 1.15
  - RMS = 1.414
  - 95% dist = 2.45



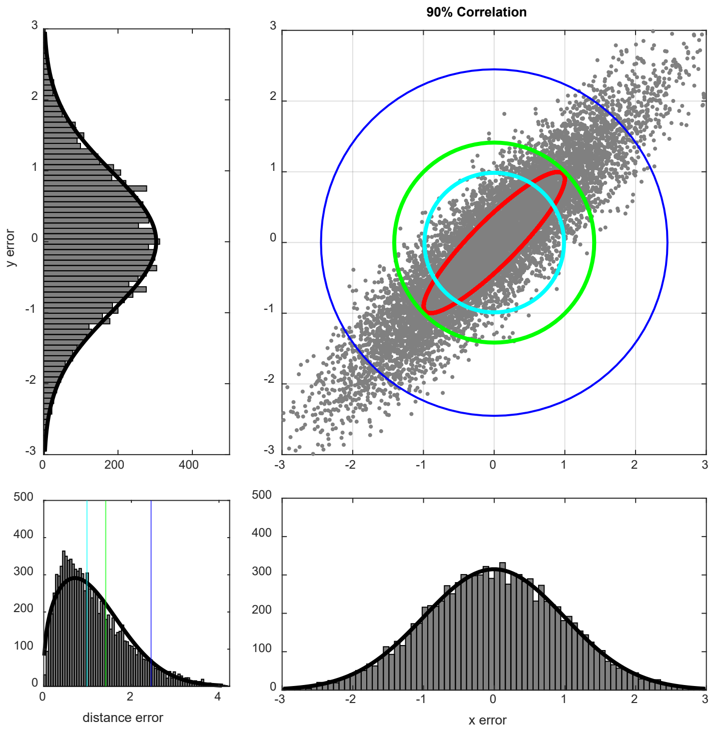
Accuracy Measures

- What about when $C_{\hat{x}}$ is not diagonal?
  - $C_x = \begin{bmatrix} 1 & 0.5 \\ 0.5 & 1 \end{bmatrix}$
  - Error Ellipse still contains 39%
  - CEP is now 1.12
  - DRMS contains 66%
  - 95% contains 94%



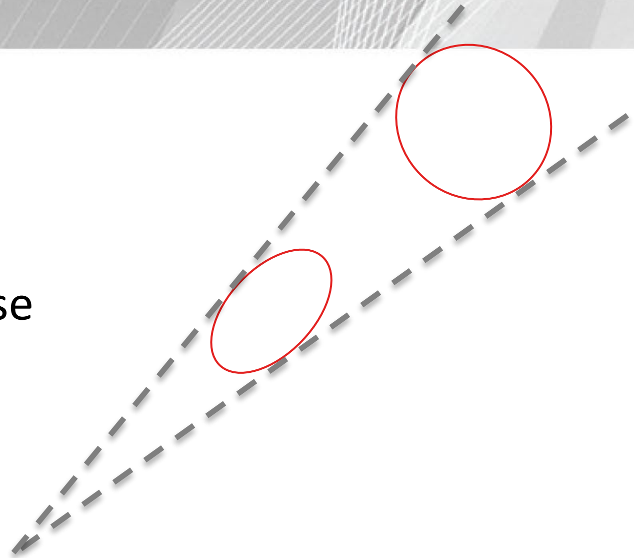
Accuracy Measures

- What about when $C_{\hat{x}}$ is not diagonal?
  - $C_x = \begin{bmatrix} 1 & 0.9 \\ 0.9 & 1 \end{bmatrix}$
  - Error Ellipse still contains 39%
  - CEP is now 0.99
  - DRMS contains 69%
  - 95% contains 92%



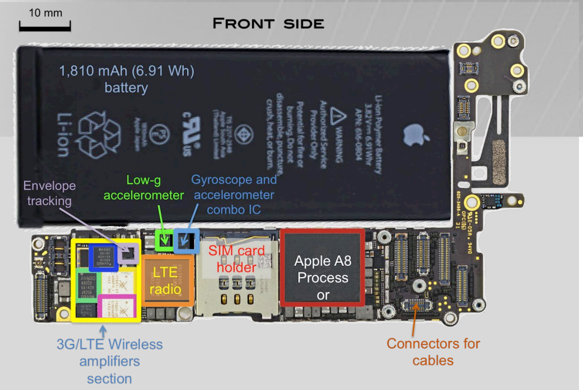
Why is this important?

- Network-based Bearing-Distance
  - Error ellipse is usually elongated
    - Angle accuracy is constant in degrees but error ellipse depends on distance from base station
- GPS
  - Horizontal usually a circle
  - Vertical is worse
  - In urban canyons across-track is bad, along track is good
  - 5 to 10 m to 2 to 4 cm depending on mode, equipment, etc.

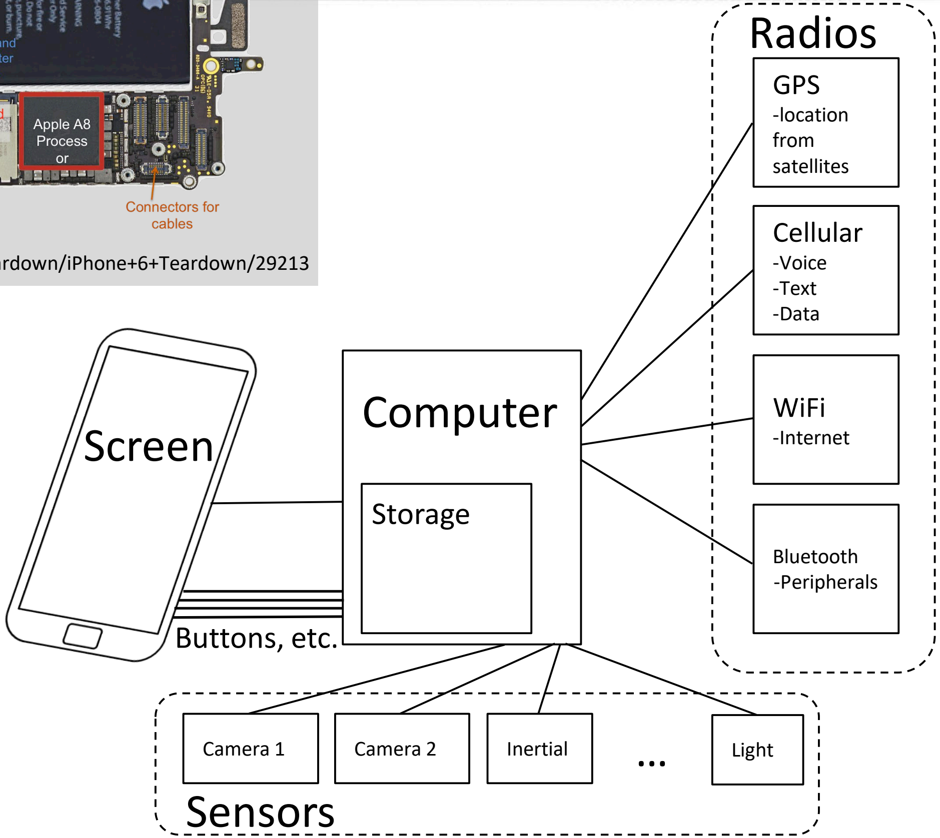


Inside a Smart Phone

- Smartphone
  - Battery
  - Computer
  - Touch Screen
  - Radios
    - GPS
    - Cellular
    - WiFi
    - Bluetooth
  - Sensors
    - Camera 1
    - Camera 2
    - Inertial
    - Magnetic
    - Pressure
    - Temperature
    - Fingerprint scanner
    - Light
  - Storage
    - Built-in
    - SD Card
    - SIM Card
  - Buttons, Jacks, Speakers, Microphones



https://www.ifixit.com/Teardown/iPhone+6+Teardown/29213



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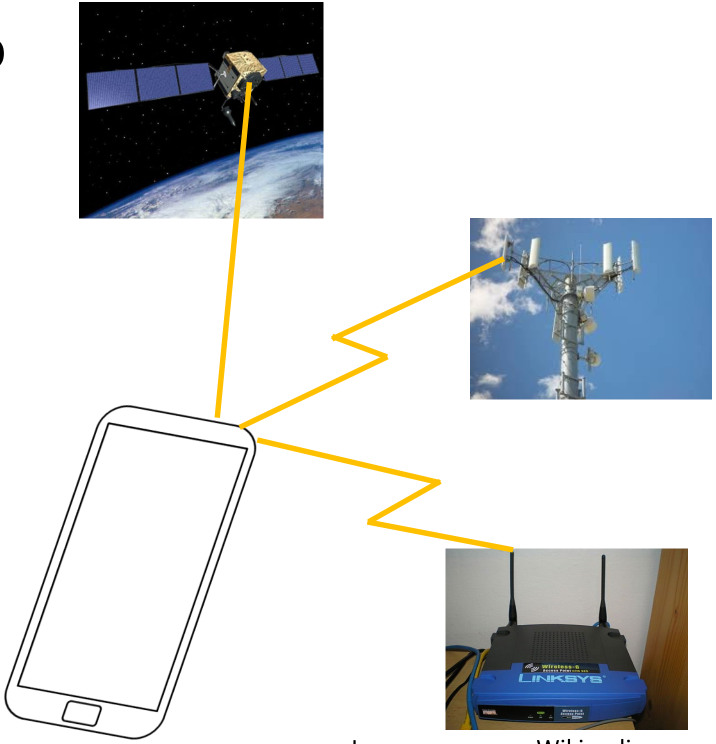
Wireless Location Methods

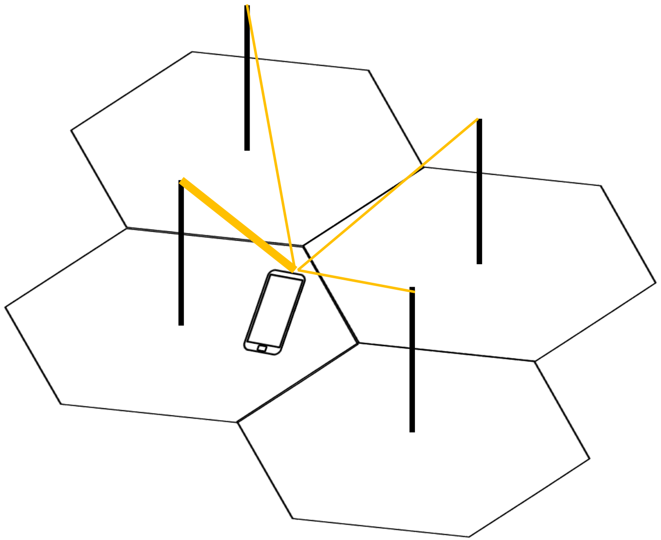
- Cell phones can be located using radio (wireless) signals
  - Three main Wireless Location methods
    1. Cellular Network
    2. GPS
    3. WiFi™ and Bluetooth™ fingerprinting
  - Other sensors can assist
    - Step/heading using inertial and magnetic sensors
    - Matching photos using artificial intelligence



Images: gps.gov, Wikipedia.org

Cellular Network Positioning

- Cellular network
  - Each tower or base station serves a "cell"
  - Cells are larger in rural areas, smaller in urban.
  - The network keeps track of tower you are connected to, power level, and sometimes direction
  - This gives the network an approximate location every phone
  - The network needs to know this so it can decide when to transfer you to a neighbouring cell
  - Normally the closest tower is handling the call and the location can be approximated as the location of the tower
    - Sometimes the closest tower may be blocked or full and the phone connects to a another nearby tower



Cellular Network Positioning

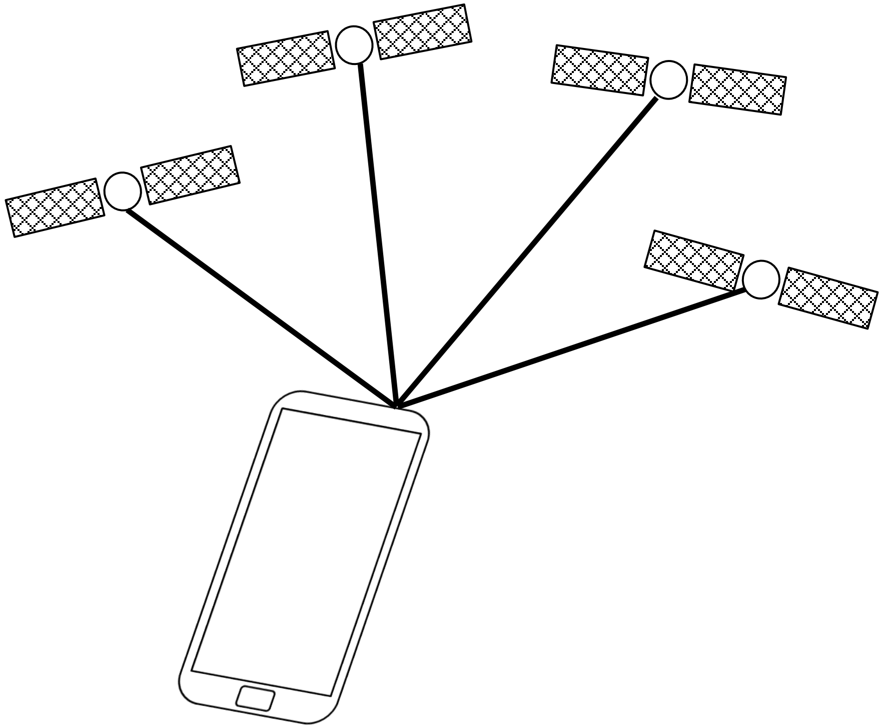
- Angle
  - Tower antennas are directional
- Range
  - 2-way time of flight
  - Power
- Proximity
  - A tower is handling the call, you are probably near there

Why Networks Need Phone Location

- The networks need to know approx. location
  - To do power control
    - Network literally tells your phone to be quiet when it's closer to the base station so it can hear the farther phones
  - To manage handoff
    - As you move from one cell to another, the call is transferred
  - Networks log data about each call
    - More about this later

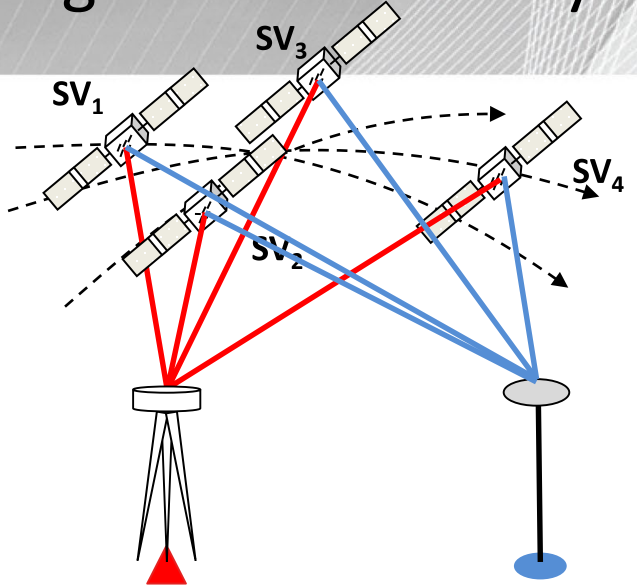
Global Navigation Satellite Systems

- The Global Positioning System is the United States Airforce constellation of about 30 satellites
  - Russia, China, Europe have their own systems
  - All phones use GPS, most include the others too
- GPS chip in phone listens for signals from 4 or more satellites
  - Satellites transmit their locations
  - Receiver chip measures time it takes for the signal to travel
  - Solves for location and time (4 unknowns)
- GPS positions generally accurate to about 5 metres in ideal conditions
  - Outdoors with a clear view of the sky
  - Affected by atmospheric errors and reflections
  - The signals are very weak and difficult to detect indoors



Global Navigation Satellite Systems

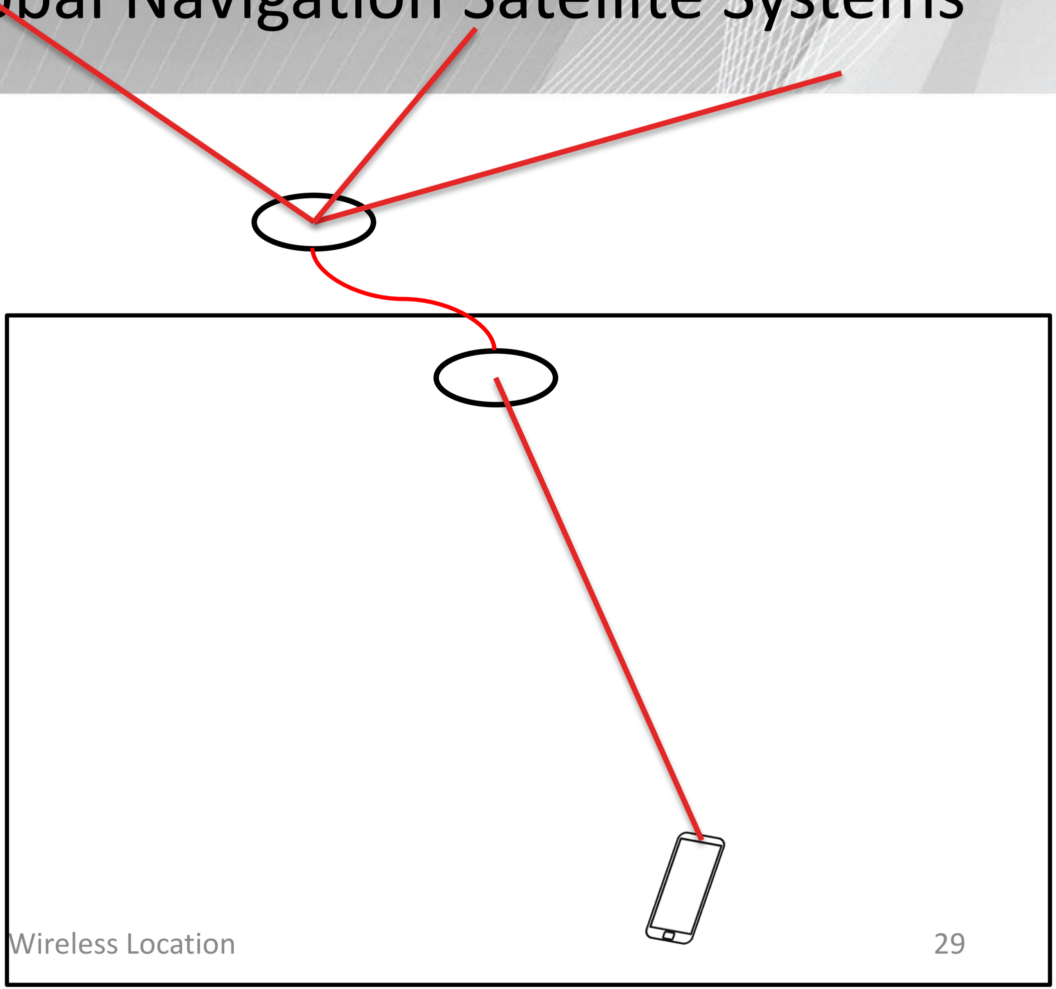
- A quick demo of how pseudoranging work



- Details
  - 4 or more pseudoranges to estimate 4 unknowns
    (x,y,z, Rx clock)
  - Pseudoranges have error (about 5 to 10 m)
    - Atmospheric delays, multipath, orbital error, etc.
  - Can be cancelled out using a nearby reference station
    - RTK 2 cm CEP.

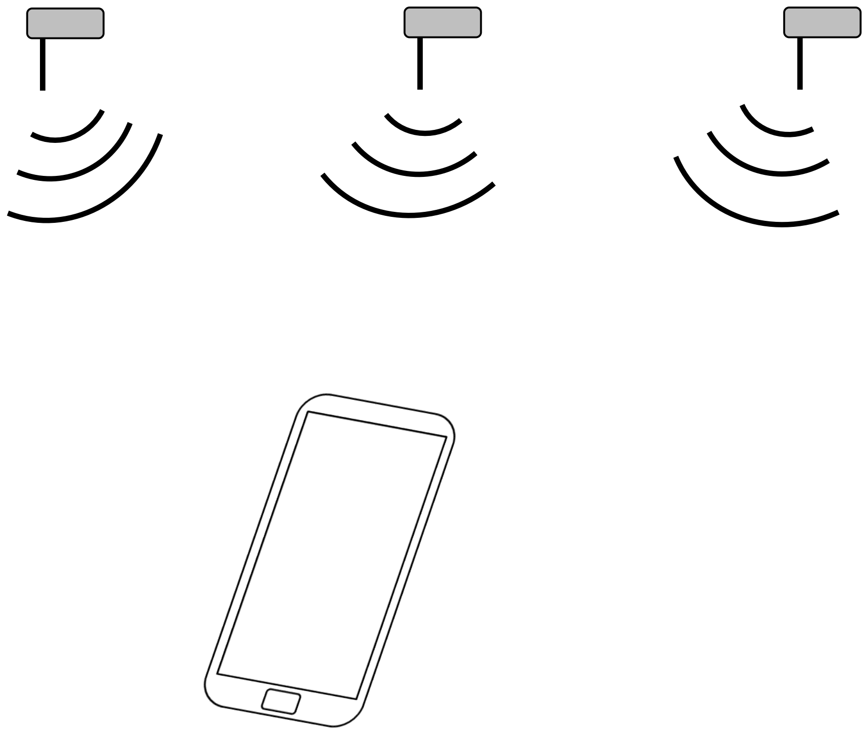
Global Navigation Satellite Systems

- Why not just rebroadcast GPS indoors?
  - Illegal in N. America
  - But done at GNSS trade shows
  - You get the position of the antenna on the roof



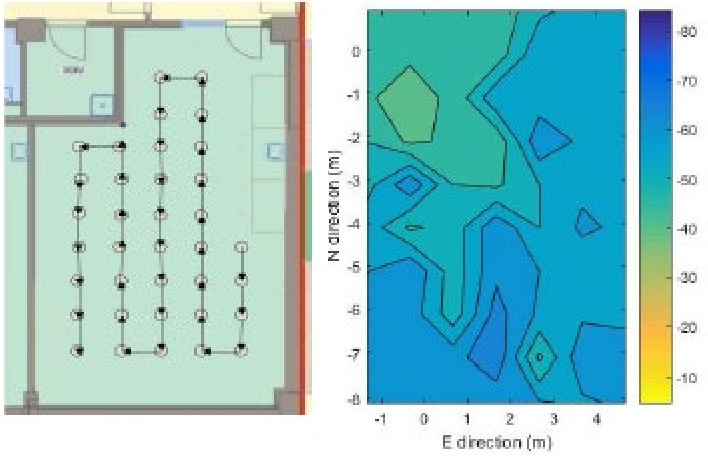
WiFi™ and Bluetooth Fingerprinting

- Phones detect nearby WiFi access points and Bluetooth devices
- Names and power levels are compared with online databases
- This process is called "WiFi Fingerprinting" because each location has a unique combination of access point names and power levels.
- Fingerprinting works best when there are many of signals.
  - Urban, commercial
  - Accuracy depends on density of access points and quality of databases
- In rural areas where WiFi is access points are sparse, fingerprinting can at least locate you within range of a single assess point, typically 50 metres
- Fingerprinting can also be done using cellular network signals



WiFi™ and Bluetooth Fingerprinting

- Many methods, most are proprietary, most based on magnitude of the RSSI difference
  - Measure a vector of RSSI values $m = [m_1 \quad m_2 \quad \ldots]^T$
  - Find values in a look-up table $t = [t_1 \quad t_2 \quad \ldots]^T$
  - Find the magnitude of the difference $|m - t|$
    - m and t are vector in RSSI dB space
    - The result is a magnitude or distance in RSSI dB space
      - This is really arbitrary and the units don't make sense
      - But it works
  - Find k entries in the table with the smallest differences
  - Position is a weighted average of the "k nearest neighbours"
- Accuracy of the map depends on
  - Number of observation points
  - Number of access points
  - Age of the data
  - Does the environment change?



from Naghdi, S., Tjhai, C., and O'Keefe, K. (2018). "Assessing a UWB RTLS as a Means for Rapid WLAN Radio Map Generation." 2018 International Conference on Indoor Positioning and Indoor Navigation (IPIN), 1–5.

WiFi™ and Bluetooth Fingerprinting

- What does the data look like?


```
{
  "considerIp": "false",
  "wifiAccessPoints": [
    {
      "macAddress": "3c:37:86:5d:75:d4",
      "signalStrength": -35,
      "signalToNoiseRatio": 0
    },
    {
      "macAddress": "94:b4:0f:fd:c1:40",
      "signalStrength": -35,
      "signalToNoiseRatio": 0
    }
  ]
}
```

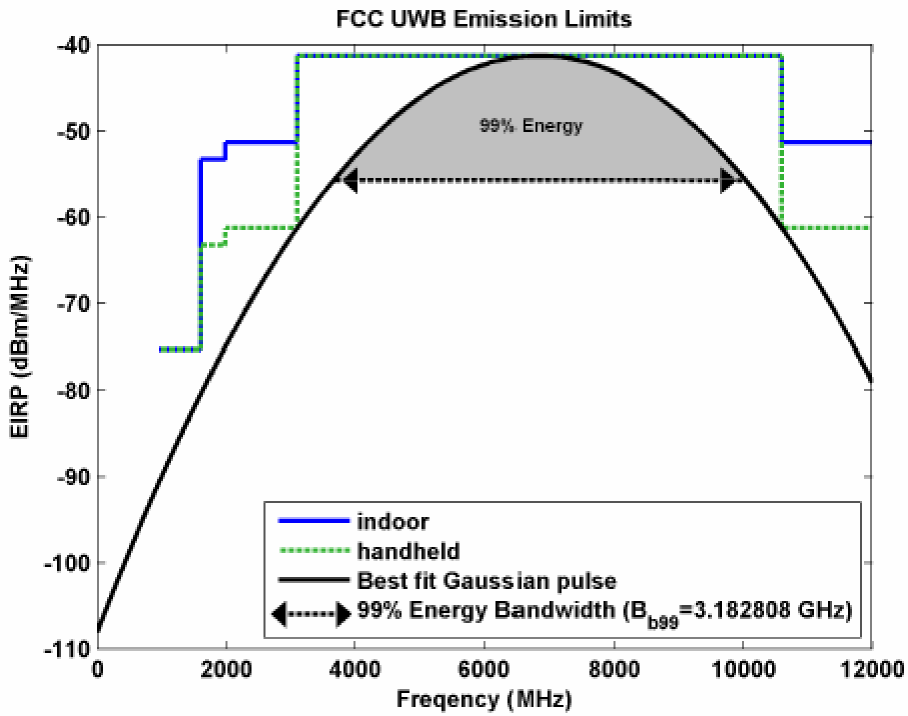

- And the response?


```
{
  "location": {
      "lat": 37.4241876,
      "lng": -122.0917381
  },
  "accuracy": 32.839
}
```


https://developers.google.com/maps/documentation/geolocation/requests-geolocation#wifi_access_point_object

UWB Ranging

- FCC Licenced UWB in 2002
  - Power levels are very low
  - Not permitted on outdoor infrastructure
  - Even lower in the 2.4 GHz band and even lower in 1.5 GHz
- A Gaussian pulse in time domain is also Gaussian in frequency domain
- A 1^{st} derivative of a Gaussian pulse will have more higher frequency components



from MacGougan (2009)

UWB Ranging

- Originally imagined as a short range high bandwidth wireless AV component protocol
- Precise ranging killer app is the AirTag™
- Android now has a UWB API

https://www.slashgear.com/1419442/samsung-smarttag2-vs-apple-airtag-comparison/

Inertial Sensors

- Newtonian mechanics can be used

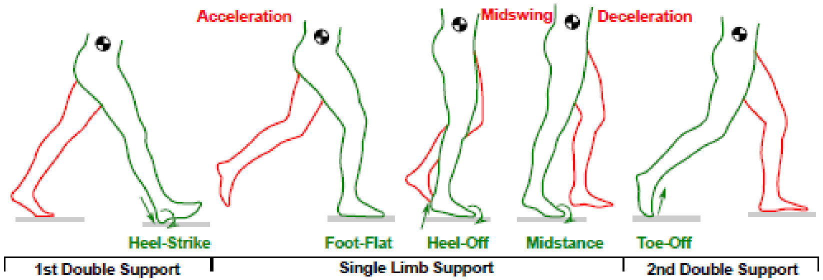
$$x = \int v + const_1$$

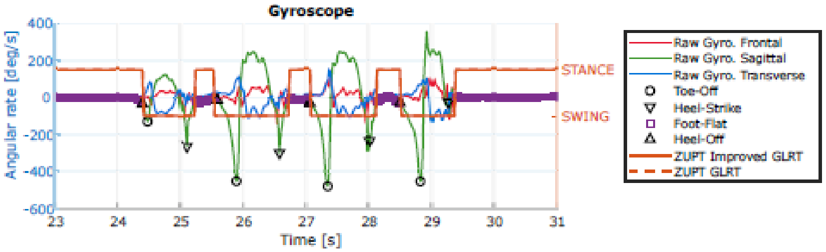
$$v = \int a + const_2$$

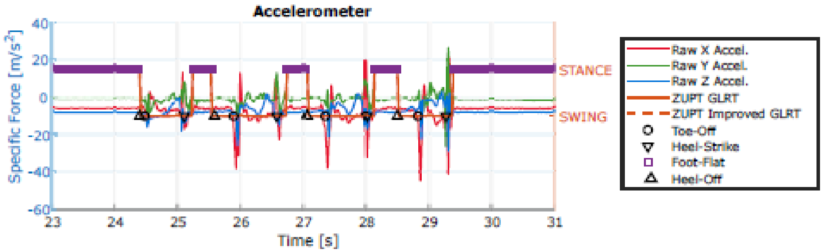
- Basic idea:
  1. Gyroscopes used to keep track of the attitude of the sensors
  2. Accelerometer data is transformed into a navigation frame
  3. Integrate to get change in velocity, integrate again to get change in position
- Given initial position and velocity, and measurements of acceleration, can determine position and velocity at any time in the future
  - But errors in the initial conditions and observations will grow over time

Inertial Sensors

- Combine with GNSS outdoors
  - Position and velocity updates reset the errors
- Do other stuff indoors
  - Pedestrian Dead Reckoning
    - Use the accels or gyros to detect steps
- Add magnetometer, barometer





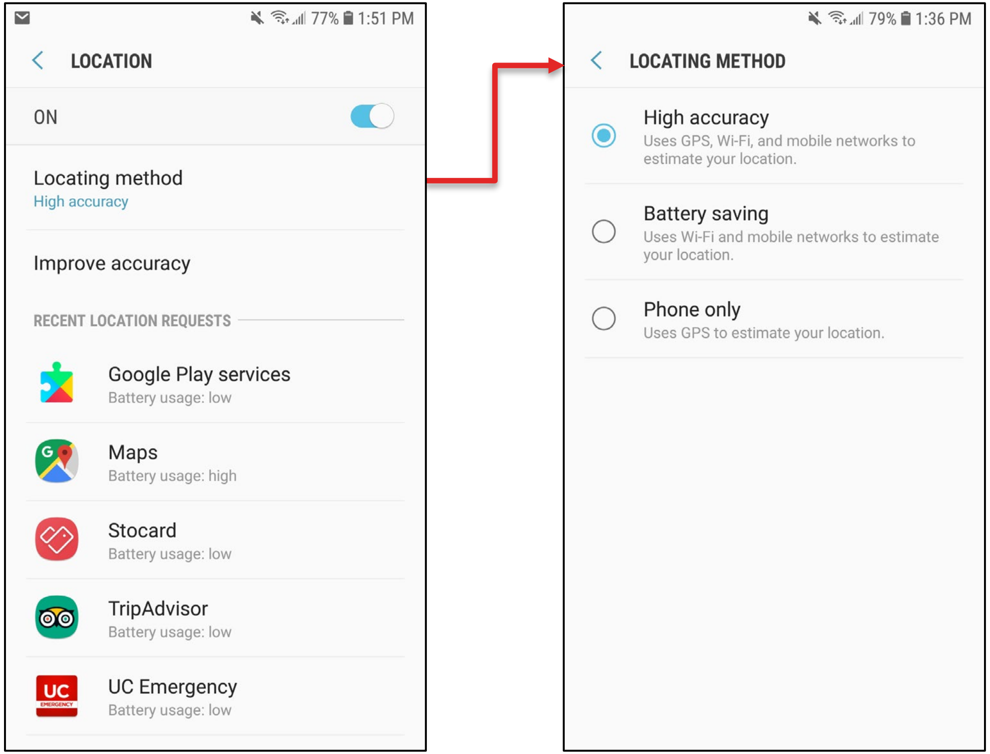


How Phones Obtain and Use Location

- An application (App) asks the operating system (OS) for a position
- The OS either:
  - Asks the GPS chip
  - Records WiFi™, Bluetooth™, and/or cellular signal information and sends a request to either a public or private database
  - May use onboard inertial or other sensors (barometer?)
- Then OS provides the response back to the App
  - The position may be displayed on the screen, recorded on the phone, or sent somewhere else

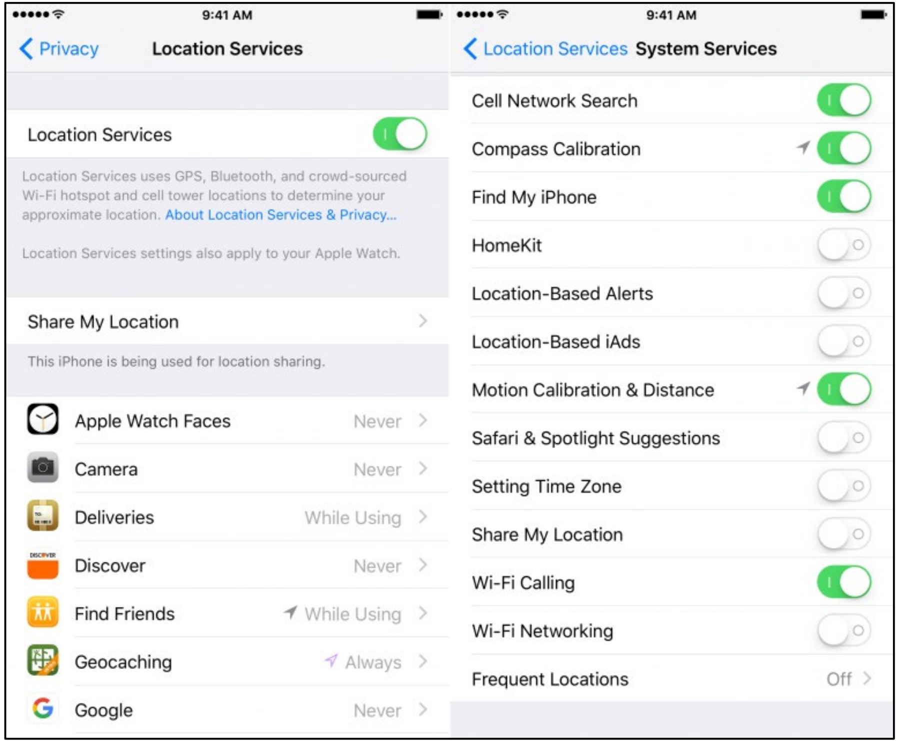
In Android

- In Android, users have some can control which method is used
  - GPS uses more battery
  - WiFi™ and mobile network method, less battery, less privacy
- Can see which Apps have made location requests recently
  - In this case: Google Maps turned on the GPS to show my location on a map.
  - Stocard is tracking where I shop
  - TripAdvisor just wants to know what part of town I'm in



In iOS

- In iOS, users don't control which method
  - iOS decides for you depending on what App you are using
- iOS does allow you to set App permissions
- Also has a list of built-in iOS location services that can be turned on and off.
  - Android also allows permissions per App and has some build-in location based services



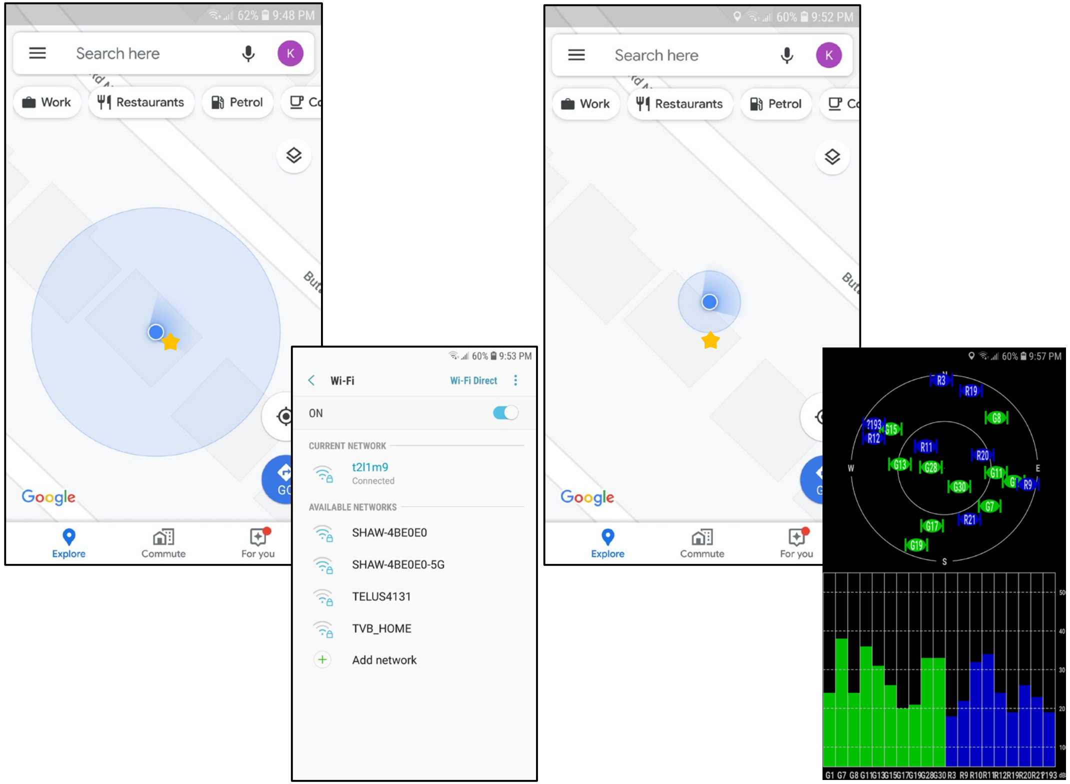
https://www.idownloadblog.com/2016/01/21/iphone-ipad-location-services/

WiFi™ vs GPS Accuracy

- GPS works best with a clear view of the sky
  - Outdoors, rural areas
- WiFi works best when there are lots of access points
  - Urban areas, malls, offices
- UWB, BLE, inertial can augment
  - For short distances
  - Or short times

Example: Main floor of a Calgary bungalow

- WiFi only
  - About 15 metres
  - Not many access points to measure
- GPS
  - About 5 metres
  - Lots of satellites
  - Still biased because user inside



Questions?

- Thank you!

- Questions?

- Contact info

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