Localisation for Mobile Devices

Dr Robert Harle

Part II Mobile and Sensor Systems

Lent 17/18

Why?

- Device mobility is fundamentally about moving through space
- So localisation is at the core of many mobile services and applications

Other applications too...

- Safety – efficient evacuation, tracking children, monitoring high risk areas (building sites etc)
- Energy Reduction – enables smart buildings to optimise heating/lighting/etc
- Space usage – allows companies to assess whether their office layouts are optimal
- Security – auto-locking doors, computers, etc
- Navigation – unfamiliar buildings, resource finding
- Collaboration – where is X? Is Y in yet?
- Resource routing – nearest telephone
- Retail – find the right item, intelligent shopping
- Health – activity level monitoring, care of elderly
- Lots of new things we haven't thought of yet...

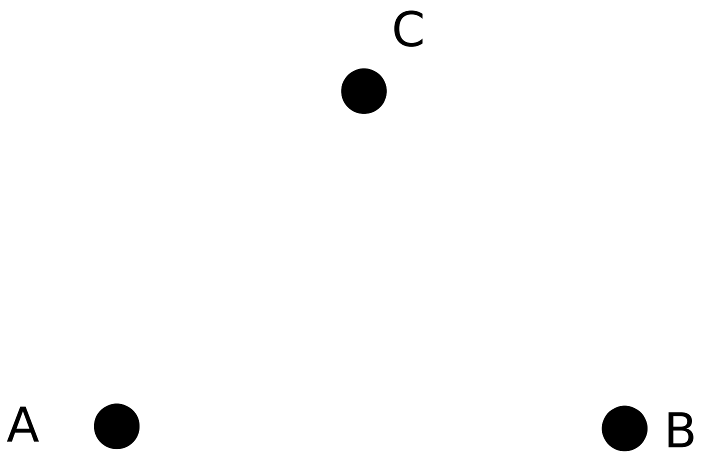
Outdoor Localisation: GPS/GNSS

GPS/GNSS is Dominant

- The Global Positioning System (GPS) was the first example of a Global Navigation Satellite System (GNSS)
- As you know, this has come to dominate outdoor localisation
- To understand it fully, we first take a slight detour to look at two important techniques...

Time of Flight (ToF)

- Measure the time taken for a signal to propagate



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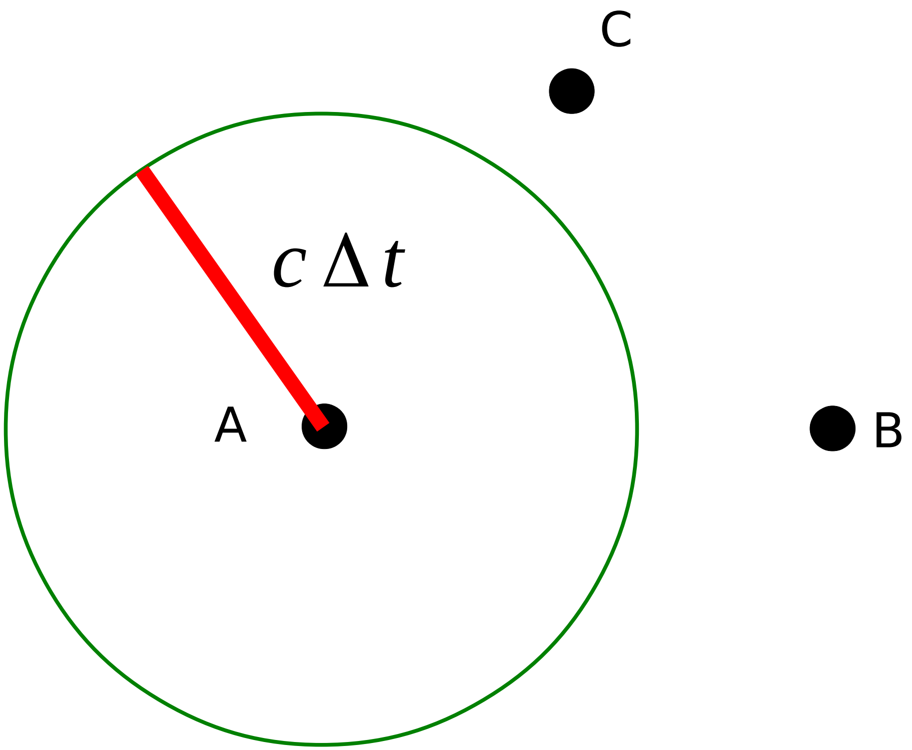

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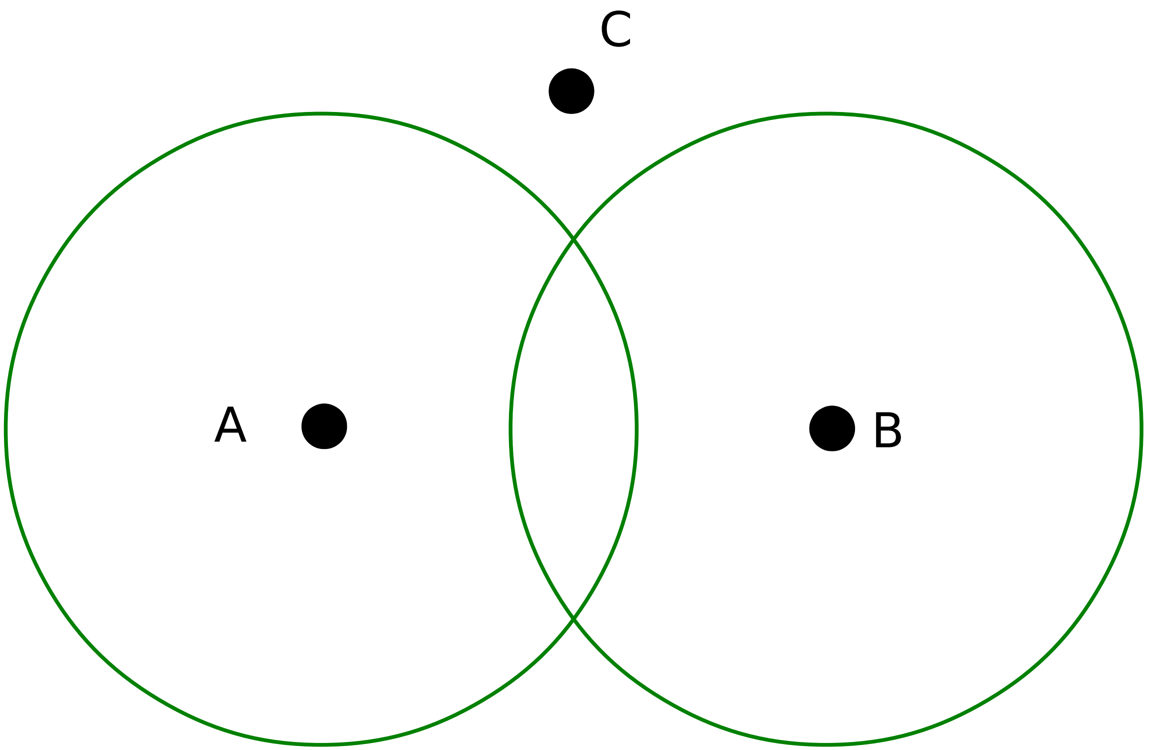

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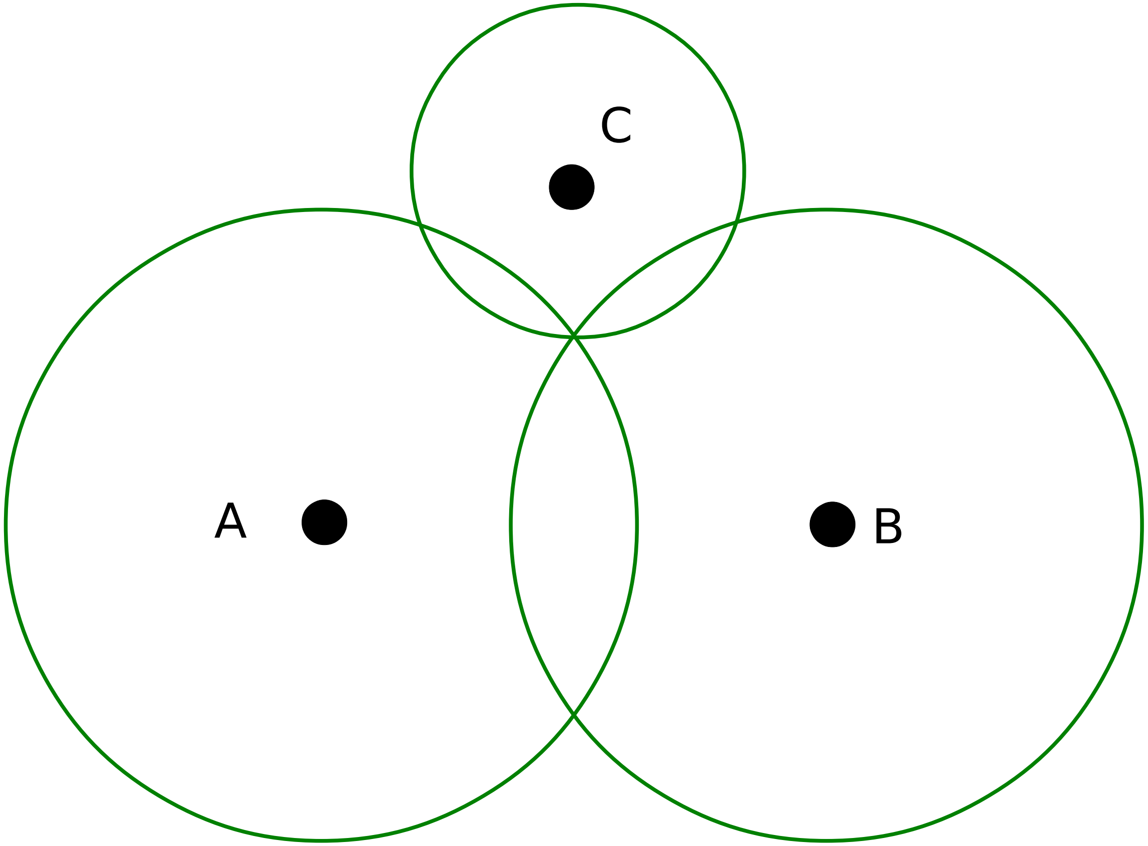

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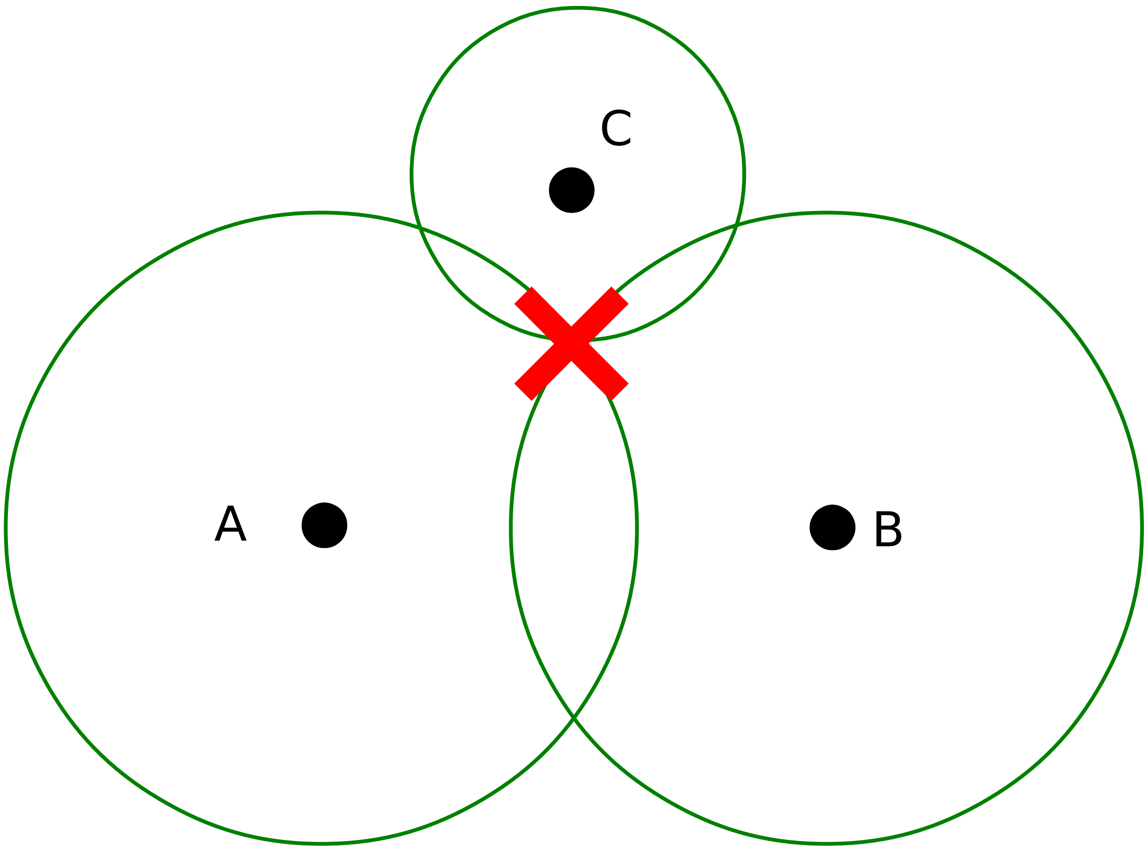
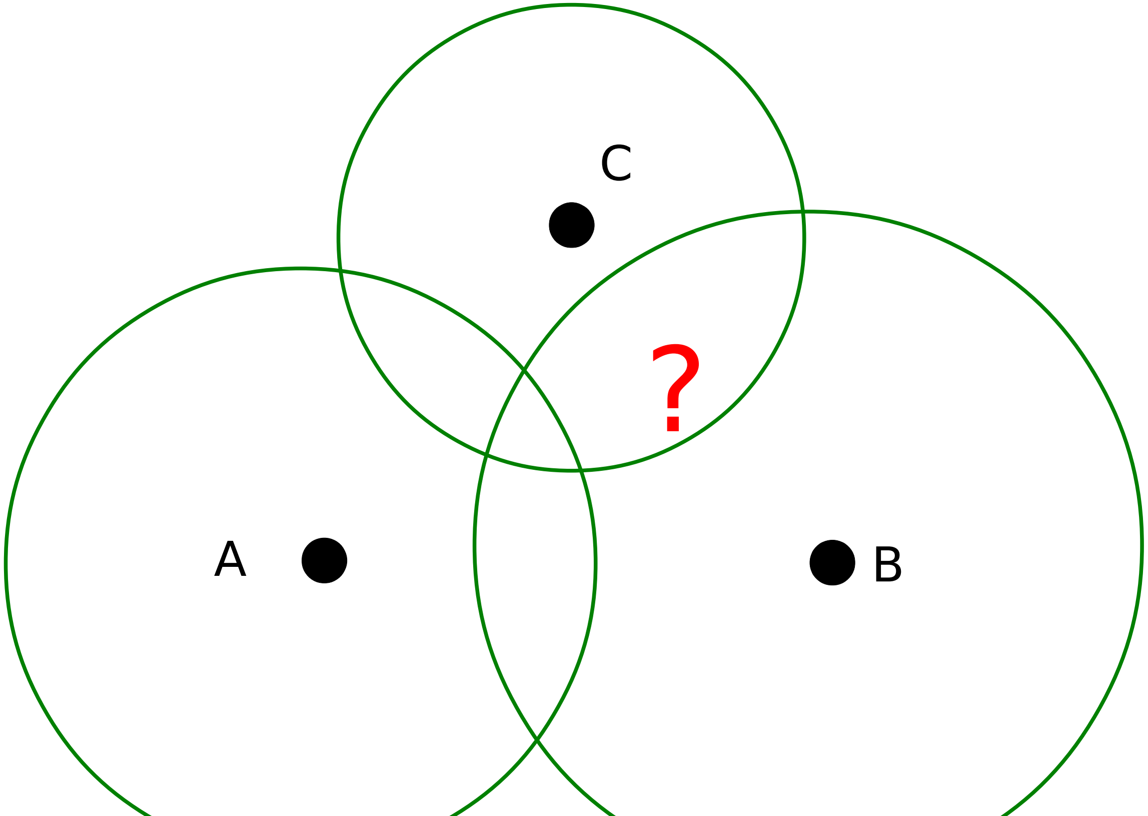


Multipath

- Multipath occurs when we don't get the direct signal but rather a reflection
- Fine for comms, but kills us in positioning since it makes distances longer than they should be



But ToF is Hard Outdoors

- We can have the mobile device as transmitter or listener, but fundamentally something has to measure the ToF, which means we need to know the transmission time
- We have a mobile device separated from the fixed sites by a <u>large</u> distance
- We can't keep the clocks synced
- Context: RF signals travel at *c*, meaning a sync error of 1 microsec is a 300m error..!

Time Difference of Arrival (TDoA)

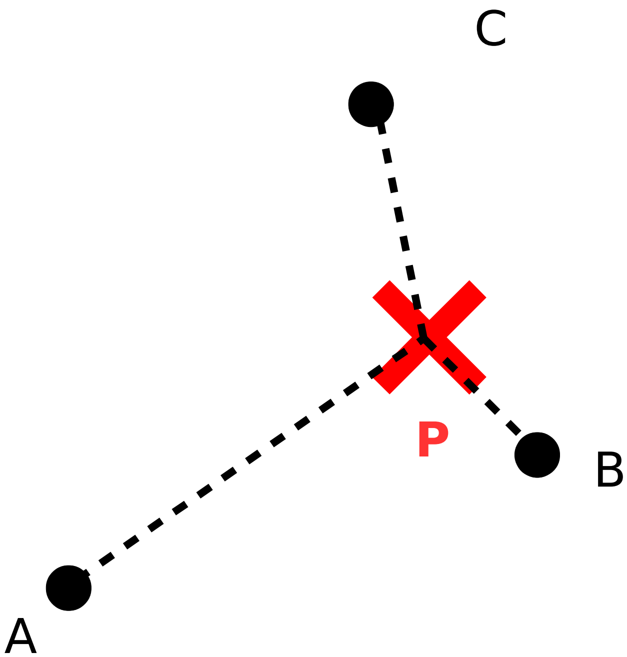
- Accept the clocks aren't synced and just try to solve for the clock offset as well (which is the same on each measurement)
- i.e. *any single range is wrong but every range is wrong by the same amount.*
- In the GPS world, these erroneous ranges are called **pseudoranges**
- An equivalent view is to consider *pairs* of received signals and look at the *difference* in time of reception (for which the clock offset error cancels)

Time Difference of Arrival (TDoA)

- Accept we can't sync the mobile and static clocks
- But we can sync all the static clocks
  - Lay a cable
  - Or use GPS (ironically)
  - Or give them all atomic clocks (ahem)

TDoA

- A,B,C have synchronised clocks
- Transmitter **sends** at unknown t_P
- A **receives** the signal at t_A, B at t_B, etc.



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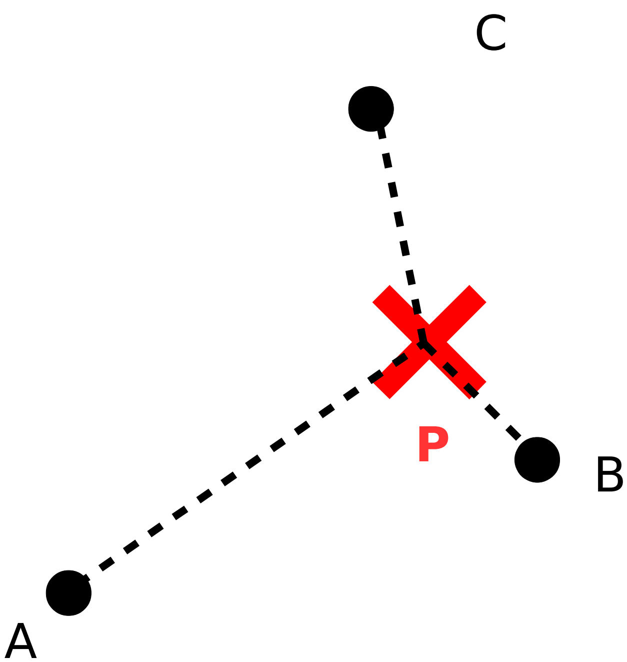

$$c(t_A - t_P) = d_{AP} \qquad (1)$$

$$c(t_C - t_P) = d_{CP} \qquad (2)$$

$$c(t_A - t_C) = (d_{AP} - d_{CP}) \qquad (1)-(2)$$

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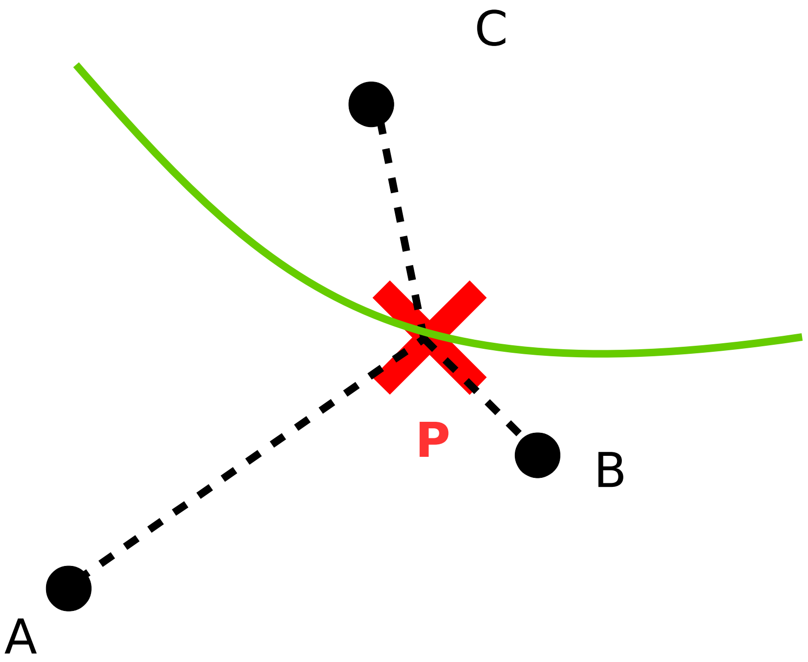

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Equation of
A hyperbola

TDoA

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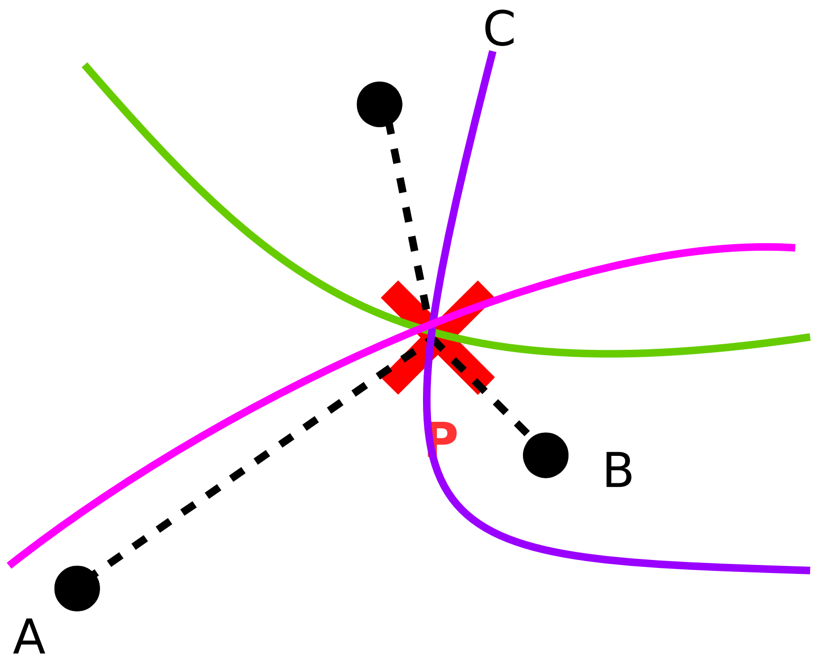


$c(t_A-t_P) = d_{AP}$

$c(t_C-t_P) = d_{CP}$

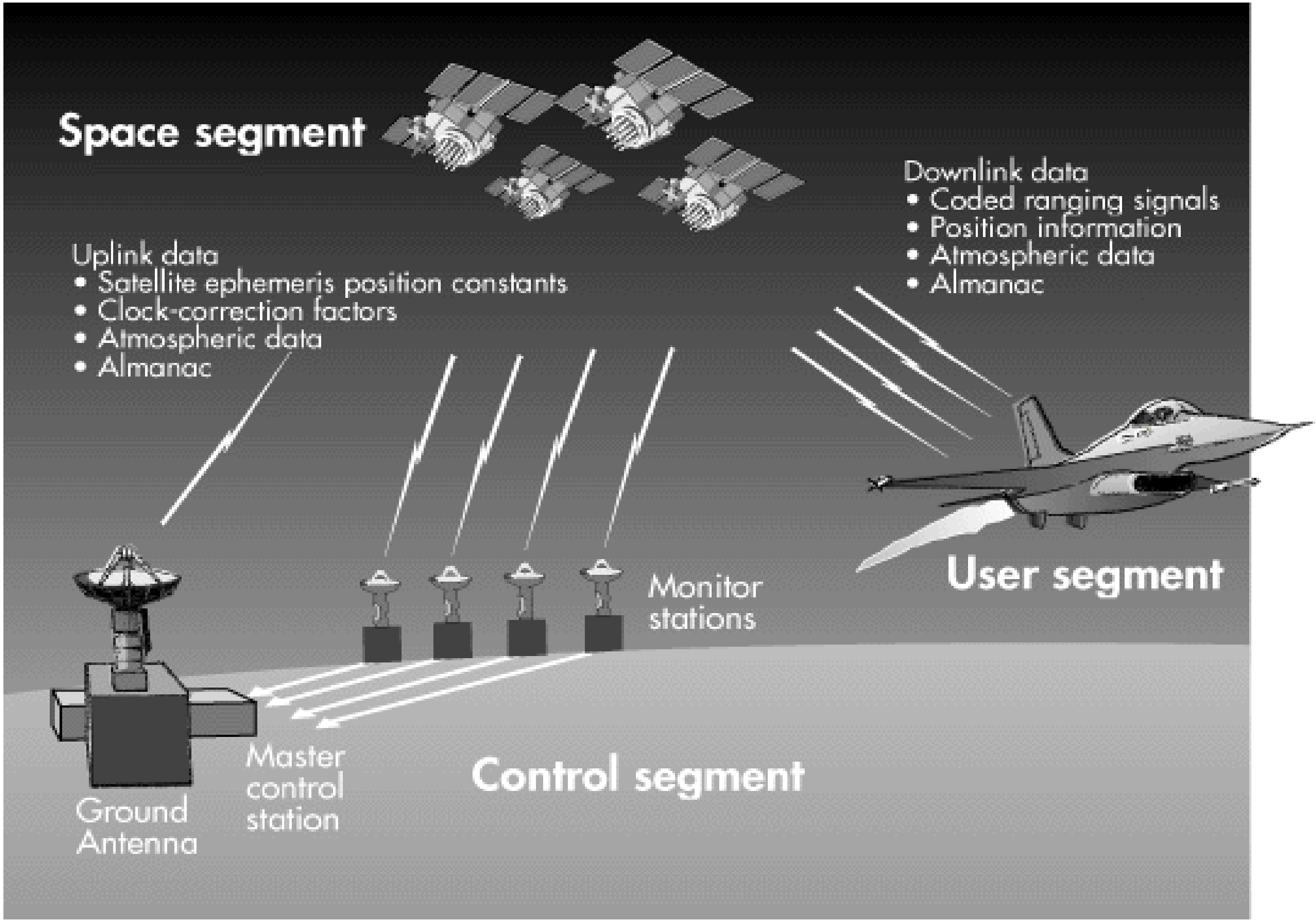
$c(t_A-t_C) = (d_{AP}-d_{CP})$

$c(t_B-t_C) = (d_{BP}-d_{CP})$

$c(t_A-t_B) = (d_{AP}-d_{BP})$

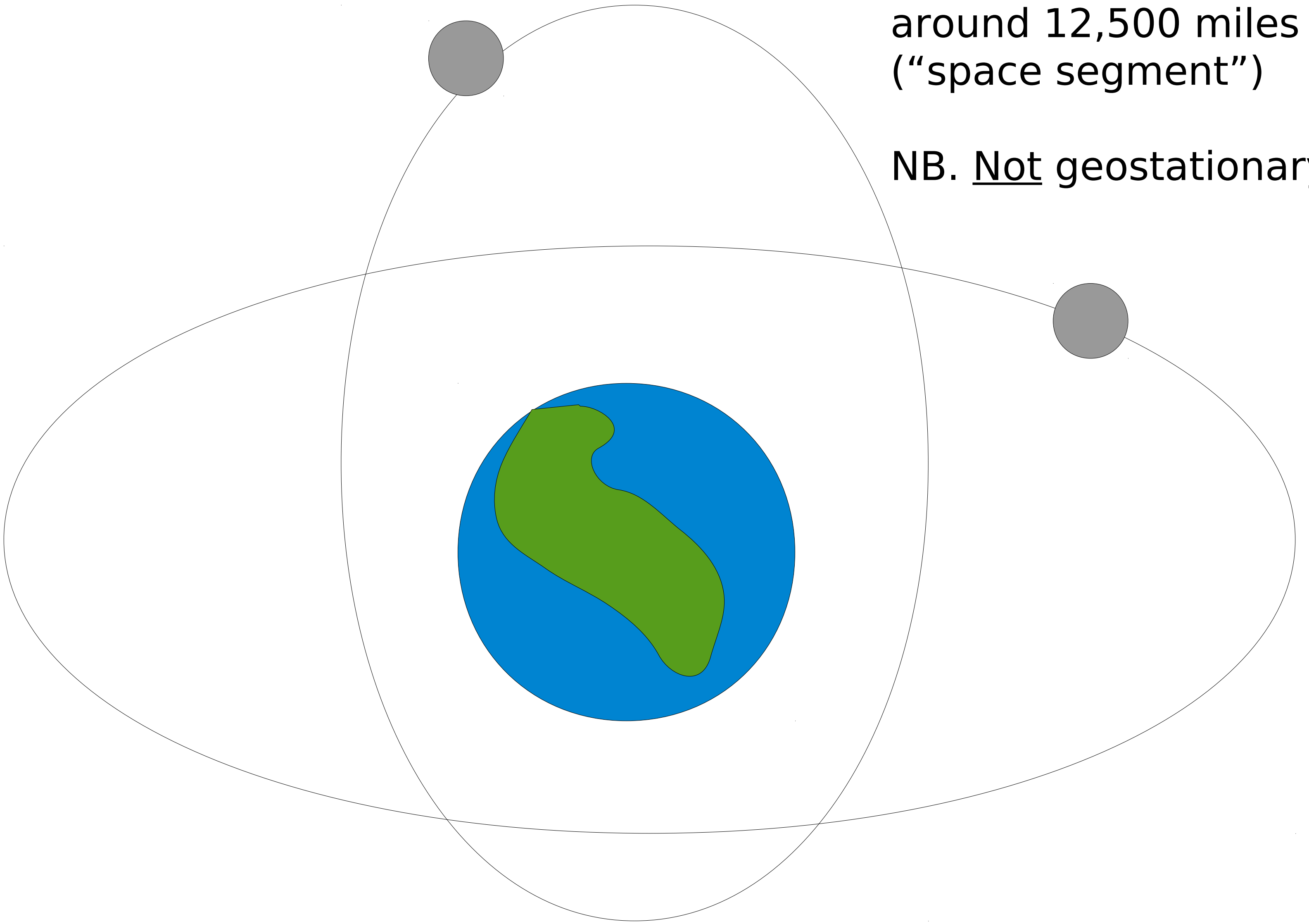
The hyperbolas intersect
at the transmitter position

Back to GPS



Space segment
Downlink data
• Coded ranging signals
• Position information
• Atmospheric data
• Almanac
Uplink data
• Satellite ephemeris position constants
• Clock-correction factors
• Atmospheric data
• Almanac
Monitor stations
User segment
Ground Antenna
Master control station
Control segment

Back to GPS



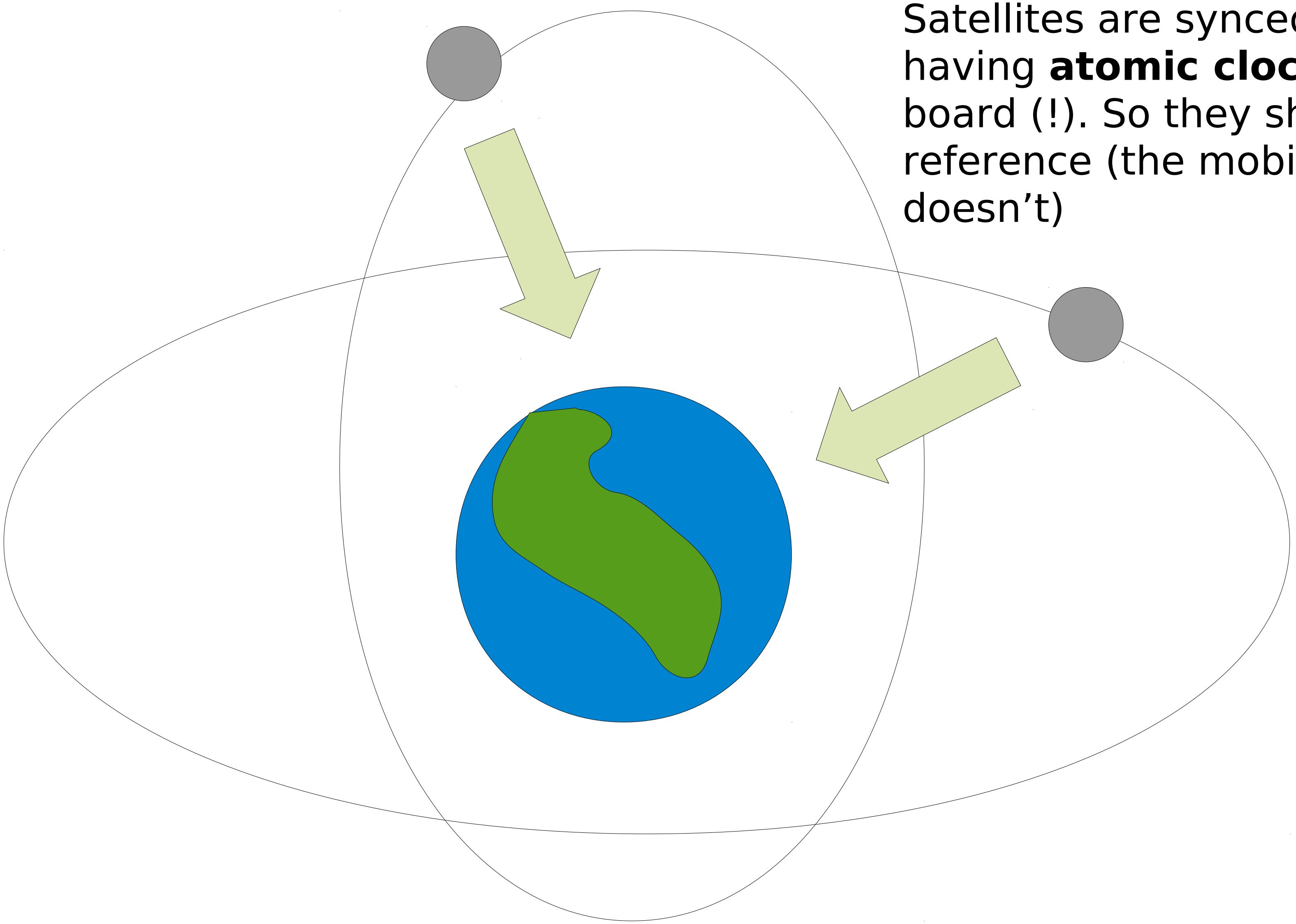
Satellites are deployed in space around 12,500 miles away ("space segment")

NB. <u>Not</u> geostationary

Back to GPS

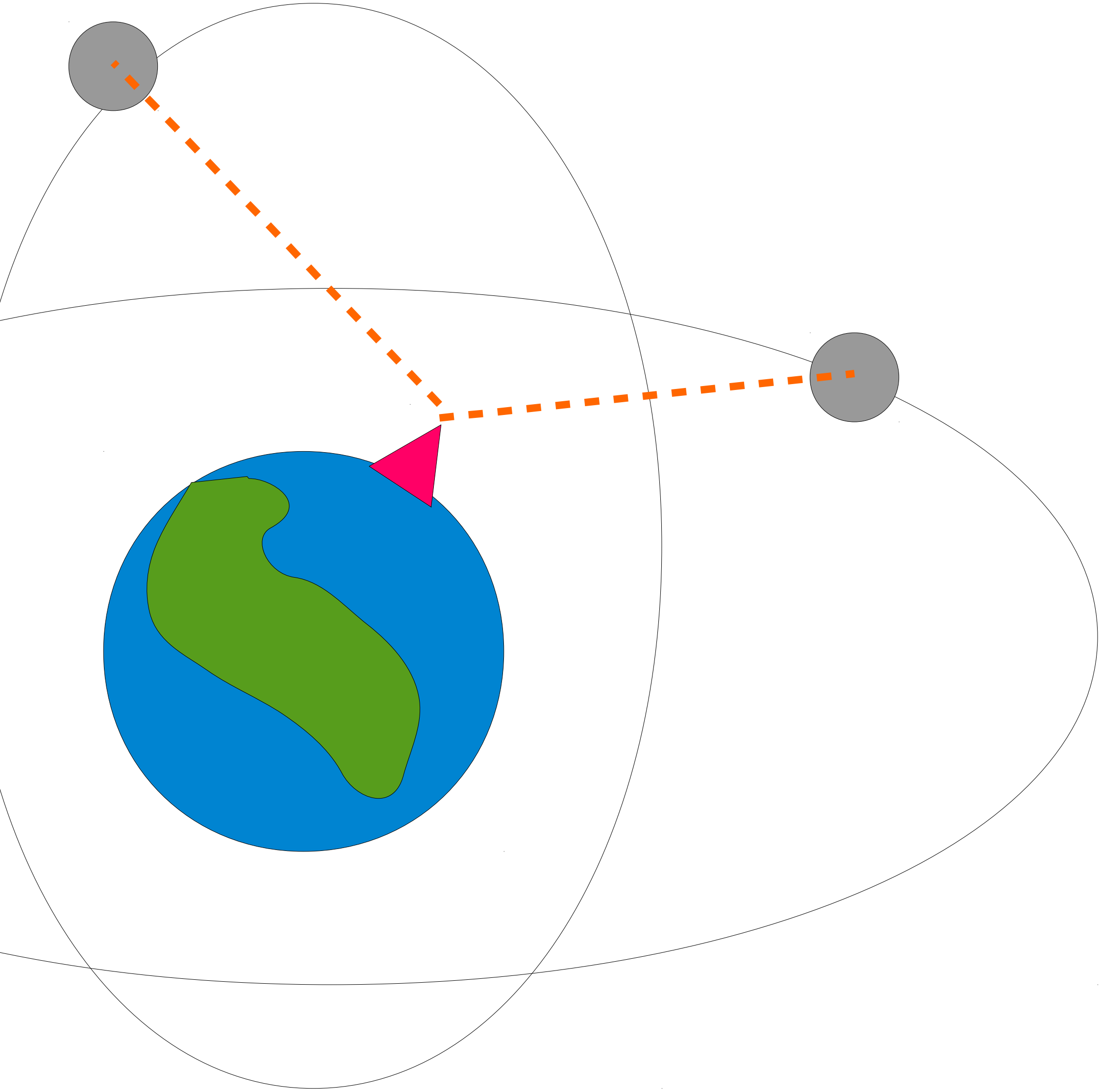
- GPS/GNSS is a TDoA system, although inverted from the model we just had
- Satellites play the part of the static devices, but are transmitters
- For each satellite the mobile device measures when it receives using its clock and uses the time the satellite says it sent for the time difference
- So for each satellite it gets a measures (ToF + c times clockOffset)
- These erroneous distances are known as pseudoranges

How are Satellites Synced?



Satellites are synced by having **atomic clocks** on board (!). So they share a time reference (the mobile device doesn't)

But They Aren't Static?



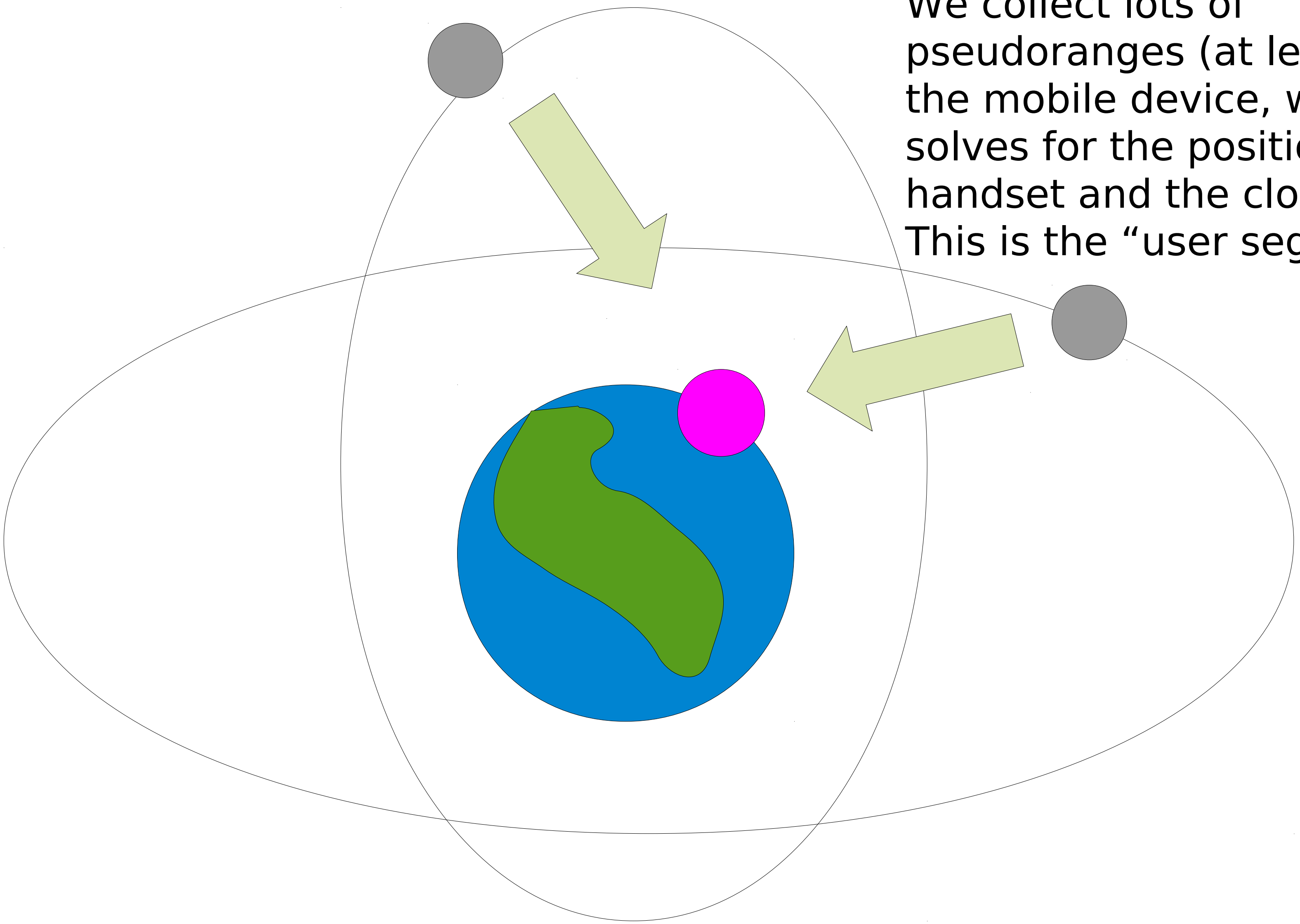
True.

Firstly we know their orbits and can predict where they are quite accurately. Although small errors creep in.

So dedicated ground stations monitor the satellite orbits so we know where they are *very* accurately. This is the "control segment"

Also has to model changes from general and special relativity!

Getting Position



We collect lots of pseudoranges (at least 4) at the mobile device, which solves for the position of the handset and the clock offset. This is the “user segment”

Position Equations

$$p_i = c \cdot \left(t_{(transmit,i)} - t_{(receive,i)} \right)$$

$$p_i = \sqrt{(x_i - x_r)^2 + (y_i - y_r)^2 + (z_i - z_r)^2} + K_i + E_i$$

- Mobile device at (x_r, y_r, z_r)
- Satellite i at (x_i, y_i, z_i)
- Clock offset between mobile and GPS time K_i
- Other errors E_i (see later)
- Four unknowns to find so we must see at least four satellites to give four equations

Error sources

- A GPS signal is sent at 20W over a distance of 12,500 miles!
- It's very weak when it hits out atmosphere and then various things interact with it → gives us the E_i term

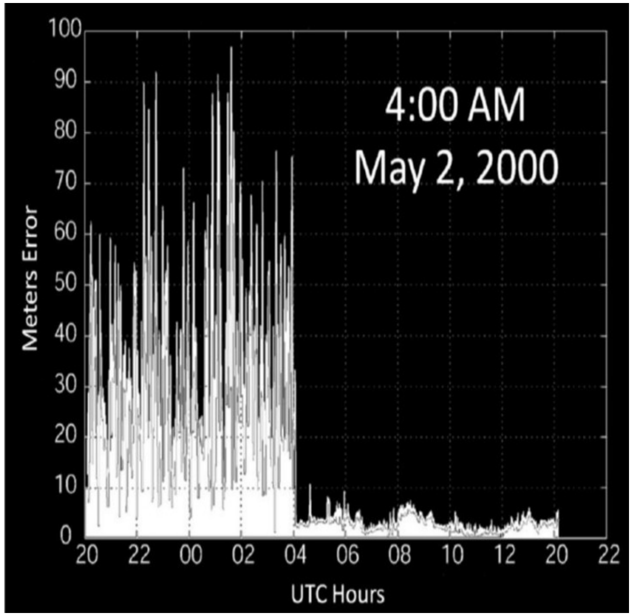
Sources of GPS error

Error cause	Error without DGPS
Ephemeris data	1.5m
Satellite clocks	1.5m
Effect of the ionosphere	3.0m
Effect of the troposphere	0.7m
Multipath reception	1.0m
Effect of the receiver	0.5m
Total RMS value	**4.0m**

- Multipath and receiver noise is relatively difficult to reduce.

http://www.soi.wide.ad.jp/class/20090061/slides/05/46.html

D-GPS



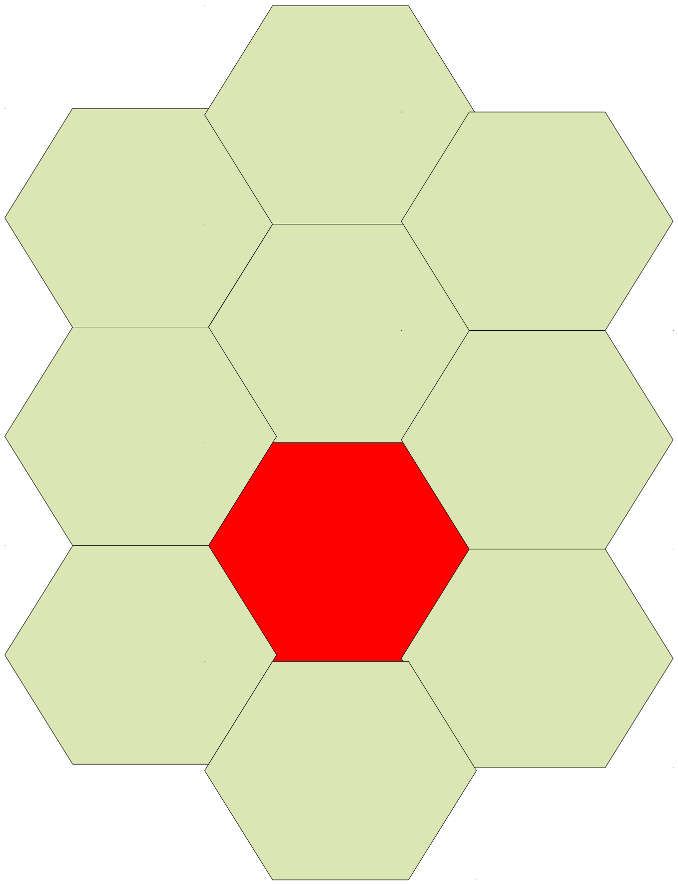
- Differential-GPS
- Put stations around the world at precisely-known locations
- Stations position themselves using GPS and compare to their known position
- Allows them to model the local GNSS errors, which they then transmit out-of-band to all local receivers so they can apply the same corrections
- Came about due to US intentionally introducing errors for security reasons ("selective availability", turned off in 2000)

Other GPS Tricks

- There is a lot to how the GPS system works – we are only scratching the surface. You might like to read about:
- Signal structure
  - the structure of the signals from the satellites (L1, L2, L5) and why we only get 50bps
- Assisted-GPS (A-GPS)
  - Getting the current motion model for each satellite ("ephemerides") takes ~20s per satellite
  - A-GPS gets those values using another link (3G, WiFi)
- Carrier Phase Positioning
  - The wavelength of the signal is about 20cm. If we can measure the phase of it, we can pull some clever tricks to get cm-level positioning.
  - For this to work we need a very accurate initial location and we need to observe the satellite movements for a little while first

Outdoor Localisation: Alternatives

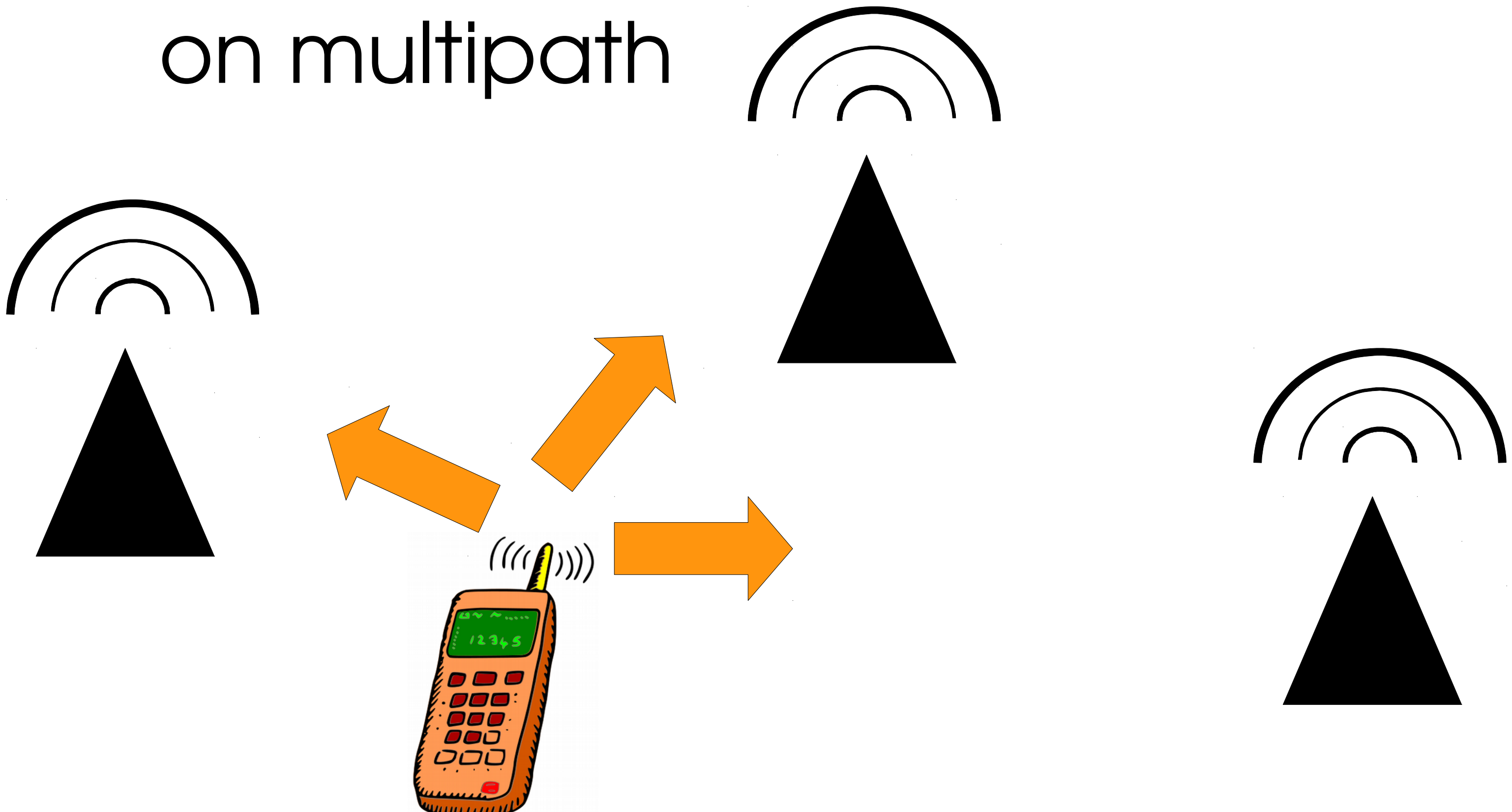
Cellular Localisation



- We deploy cellular systems
- A handset must register with a base station
- That registration gives coarse proximity
- Coarseness depends on area type (rural/city/etc)
- Often km

U-TDoA

- Apply TDoA to the phone network. Base stations use GPS to sync.
- Anywhere from 30m-400m depending on multipath



Indoor Localisation

Indoor Localisation

- GPS is fantastic outdoors but the signals don't penetrate well enough indoors.
- But people spend the majority of their time indoors so location here potentially very valuable
- Indoors is more problematic
  - Can't easily deploy a <u>ubiquitous</u> signal
  - The scale changed. 3m outdoors is more than sufficient, but 3m indoors doesn't even put you in the correct room: 10m is mostly useless. So core GPS not much use even if it did work.
  - Many objects → reflections → multipath

Indoor Location from Proximity (“microlocation”)

Proximity location is simple

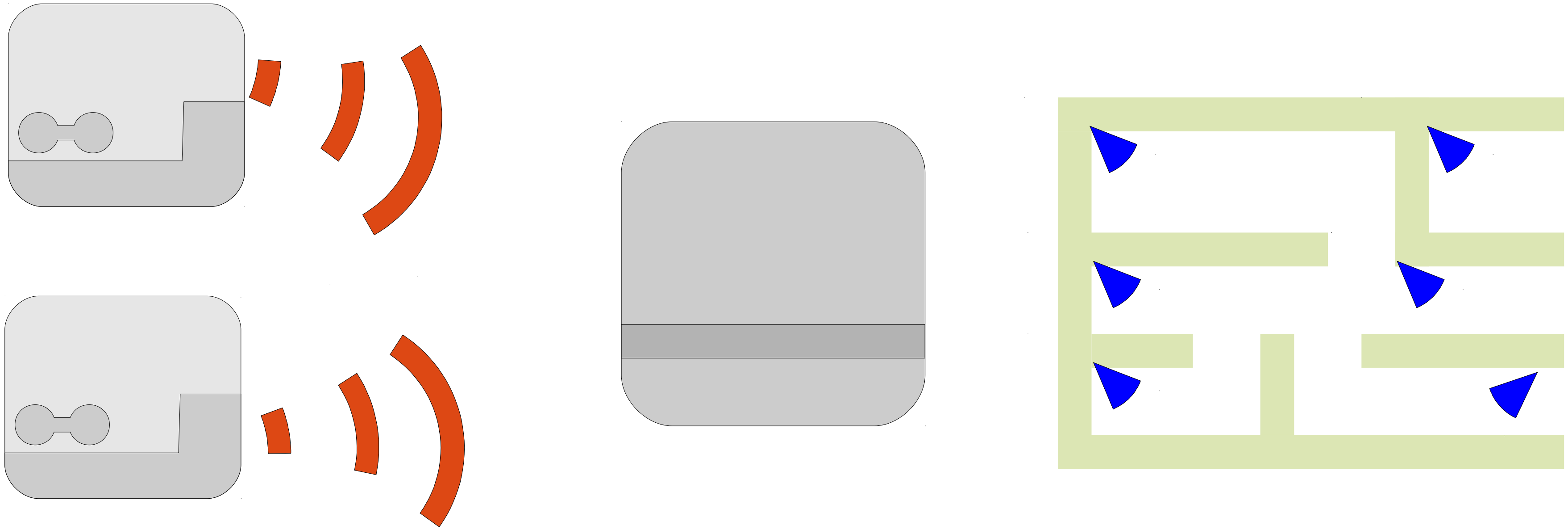
- I have limited range. I can hear you therefore you are nearby.
- The original indoor solution but fell from favour
- Now coming back with a vengeance and a new name: *microlocation*

The Active Badge

- The motivation for the first real indoor location system was proximity-based telephone call routing.
- The ORL lab (later became AT&T) wanted calls routed to them wherever they were in the building

Using Infra-red

- Each badge transmitted its ID using IR in a way analogous to your TV remote. Sensors installed in the environment listened for the IDs.
- Provided room-scale proximity location



1990...

ORL/STL Active Badge Project

Name	Location	Prob.	Name	Location	Prob.
P Ainsworth	X343 Accs	100%	J Martin	X310 Mc Rm	100%
T Blackie	X222 DVI Rm.	80%	O Mason	X307 Lab	77%
M Chopping	X410 R302	TUE.	D Milway	X307 Drill	AWAY
D Clarke	X316 R321	10:30	B Miners	X202 DVI Rm.	10:40
V Falcao	X218 R435	AWAY	P Mital	X213 PM	11:20
D Garnett	X232 R310	100%	J Porter	X398 Lib.	100%
J Gibbons	X0 Rec.	AWAY	B Robertson	X307 Lab	100%
D Greaves	X304 F3	MON.	C Turner	X307 Lab.	MON.
A Hopper	X434 AH	100%	R Want	X309 Meet. Rm.	77%
A Jackson	X308 AJ	90%	M Wilkes	X300 MW	100%
A Jones	X210 Coffee	100%	I Wilson	X307 Lab.	100%
T King	X309 Meet. Rm.	11:20	S Wray	X204 SW	11:20
D Lioupis	X304 R311	100%	K Zielinski	X402 Coffee	100%

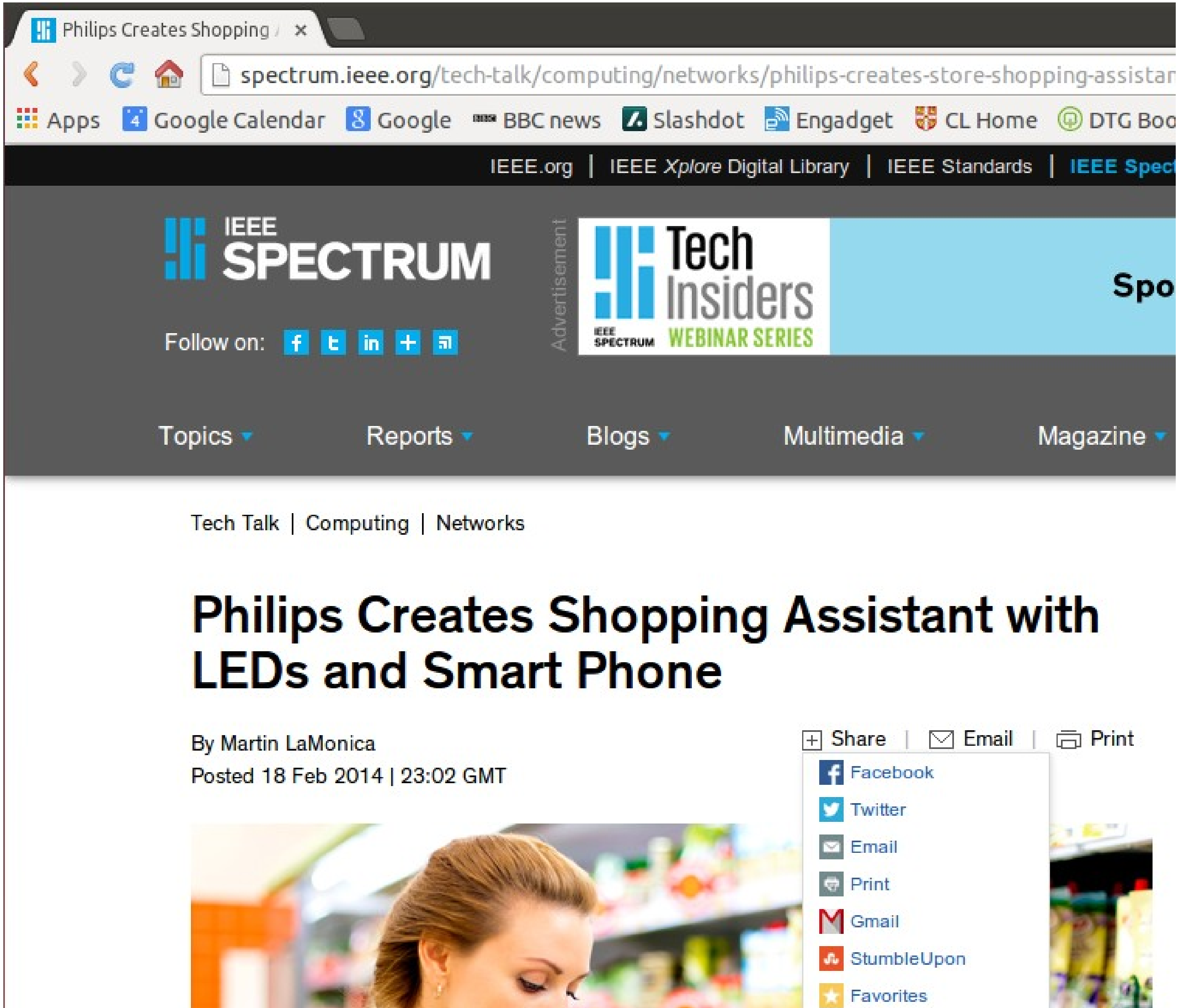
12.00 1st January 1990

BLE/iBeacons

- Bluetooth Low Energy (BLE) has an advertising mechanism that can be used to place anchors, or 'beacons' for location
- Handset sees beacon → looks up beacon position → assumes it is there. Beacon range 1-3m.
- BLE compelling here because easy to deploy (batteries); minimal maintenance (beacons long lasting); small packages; cheap; widely supported

Image from ibeacon.com

Philips



Philips Creates Shopping /

spectrum.ieee.org/tech-talk/computing/networks/philips-creates-store-shopping-assistar

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Philips Creates Shopping Assistant with LEDs and Smart Phone

By Martin LaMonica
Posted 18 Feb 2014 | 23:02 GMT

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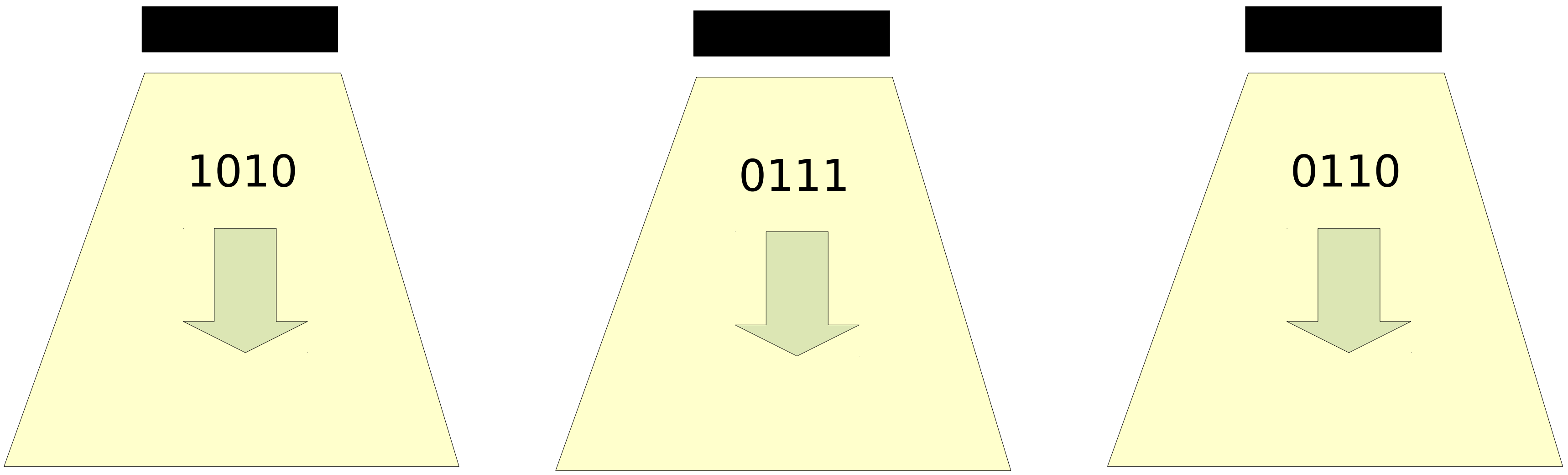
Philips

- LED light flickers faster than we can perceive with our eyes
- Phone camera can decode ID → position



Cunning use of smartphone camera

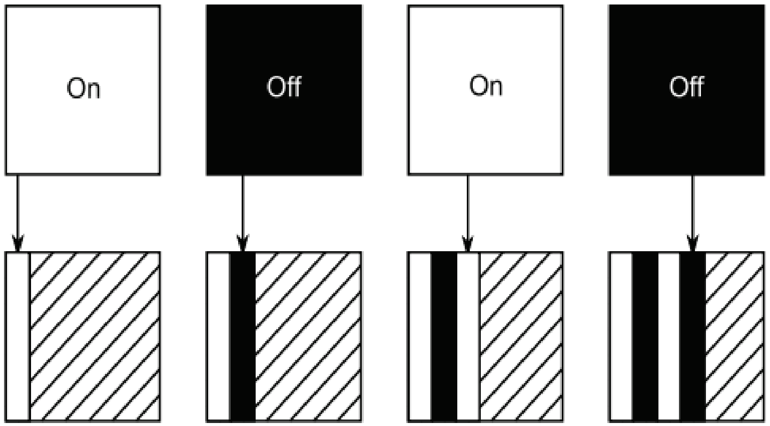


Fig. 3. Rolling shutter operation: The top squares indicate the state of the LED light. The bottom squares show the output of the CMOS camera as it enables one scanline at a time, forming the final image.

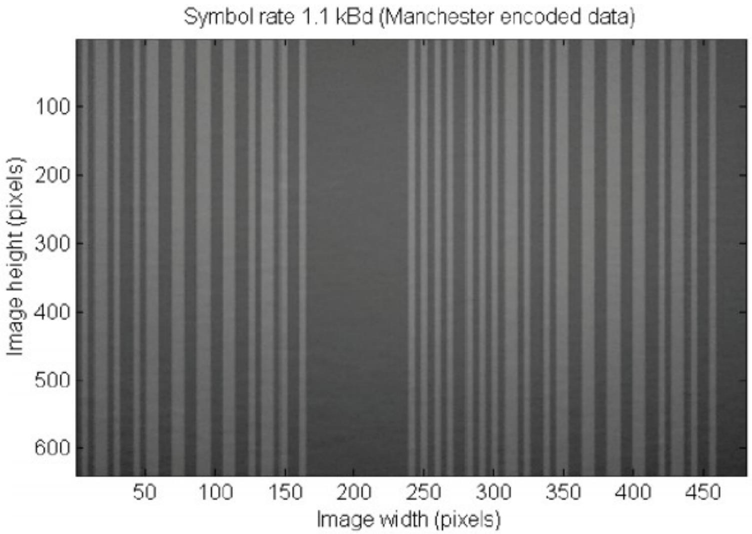


Fig. 4. Sample image of CMOS camera output – The result of the rolling shutter as taken from the preview mode of the Dell Streak mobile phone (at 1.1 kBd transmitted baud rate).

. Danakis, M. Afgani, G. Povey, I. Underwood and H. Haas, "Using a CMOS camera sensor for visible light communication," 2012 IEEE Globecom Workshops, Anaheim, CA, 2012, pp. 1244-1248. URL: http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=6477759&isnumber=6477486

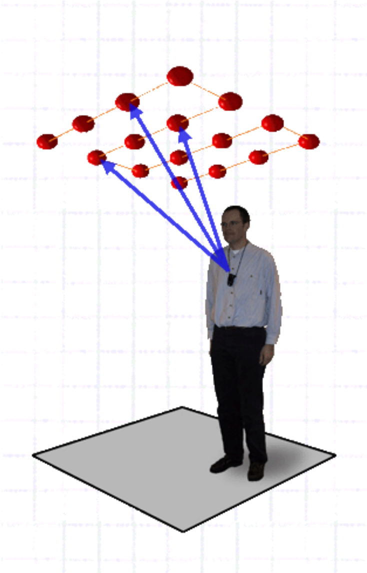
Indoor Localisation from Time of Flight

Time-of-Flight

- Time of Flight was useless outdoors because we couldn't sync all the devices.
- Indoors the scale is smaller and we can avoid sync issues using slow (but short range) signals such as sound...

The Bat System

- Developed in Cambridge (CUED/AT&T Research Cambridge)
- System starts clock and emits 433 MHz radio pulse
- Bat receives pulse and emits 50 Hz ultrasonic pulse
- Ceiling receivers measure pulse reception times
- Achieves **3cm accuracy 95% of the time in 3D!**



Ultrasound

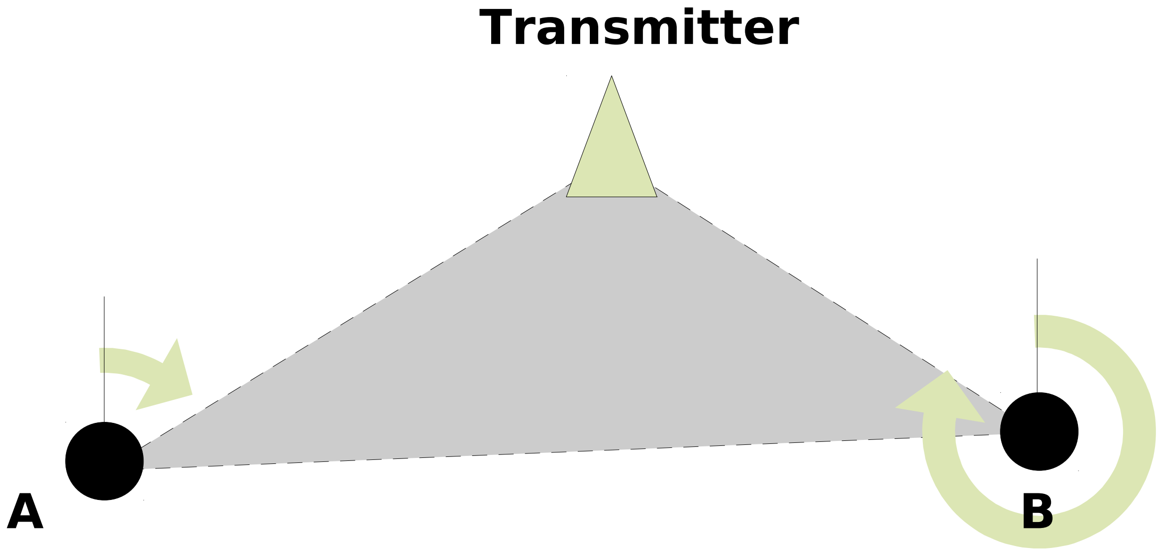
+ Can be timed because it's so slow
+ Contained by rooms

- Limits update rate
- Need Line of Sight
- Lots of *surveyed* receivers
- It's not silent to everything..!
- Easy to jam!
- Ultimately too expensive to deploy

Indoor Localisation from Angulation

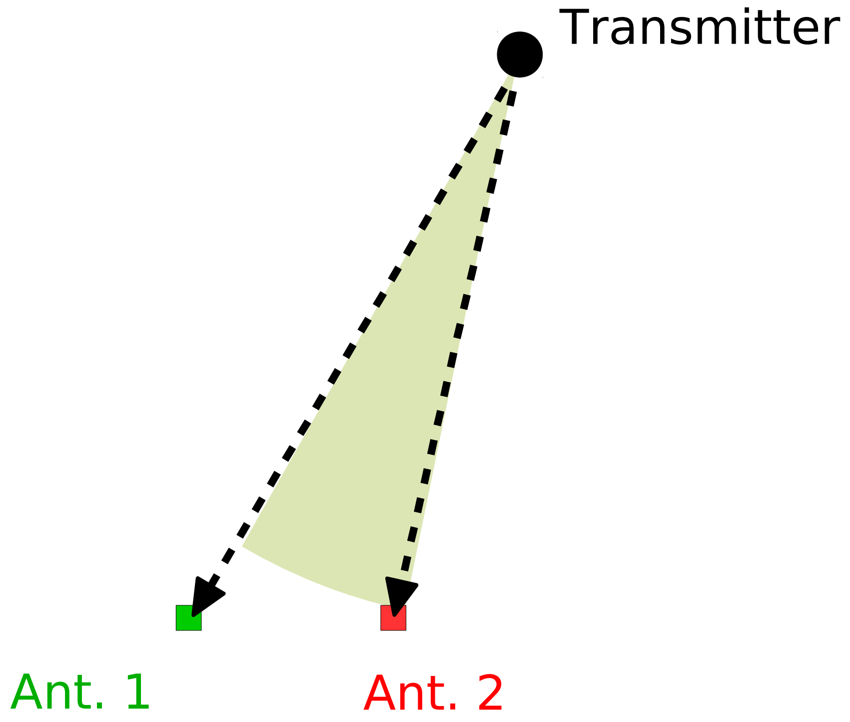
Angle of Arrival (AoA)

If you can sense direction then measure the bearing to a transmitter from different places. This is tri-angulation.



Radio: Phased Arrays

Use a phased array (= multiple antennas with special spacing) to measure the AoA



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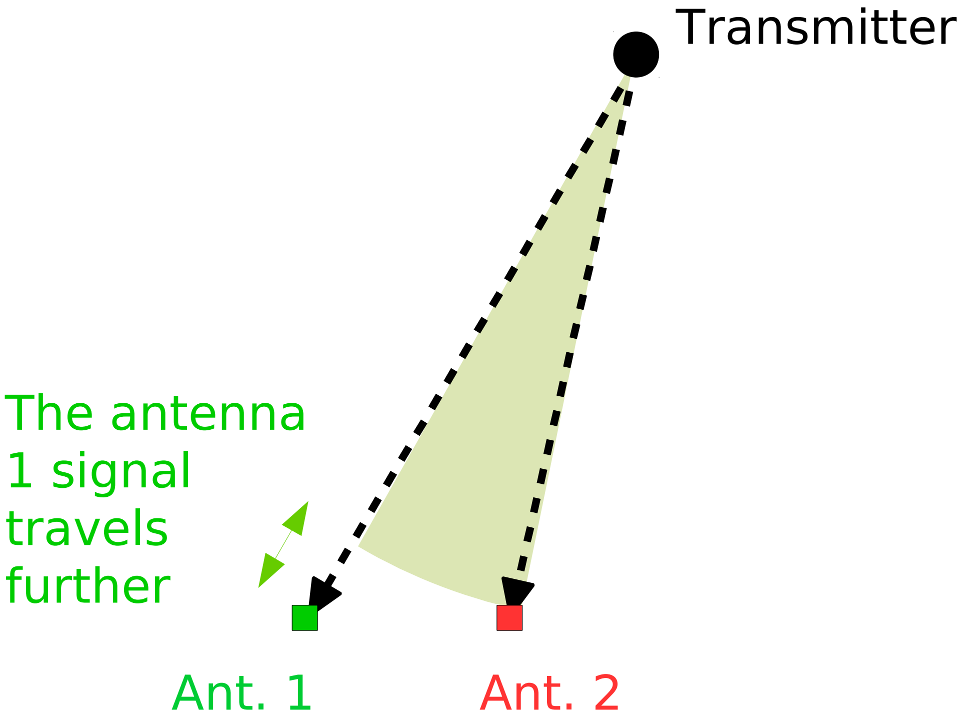

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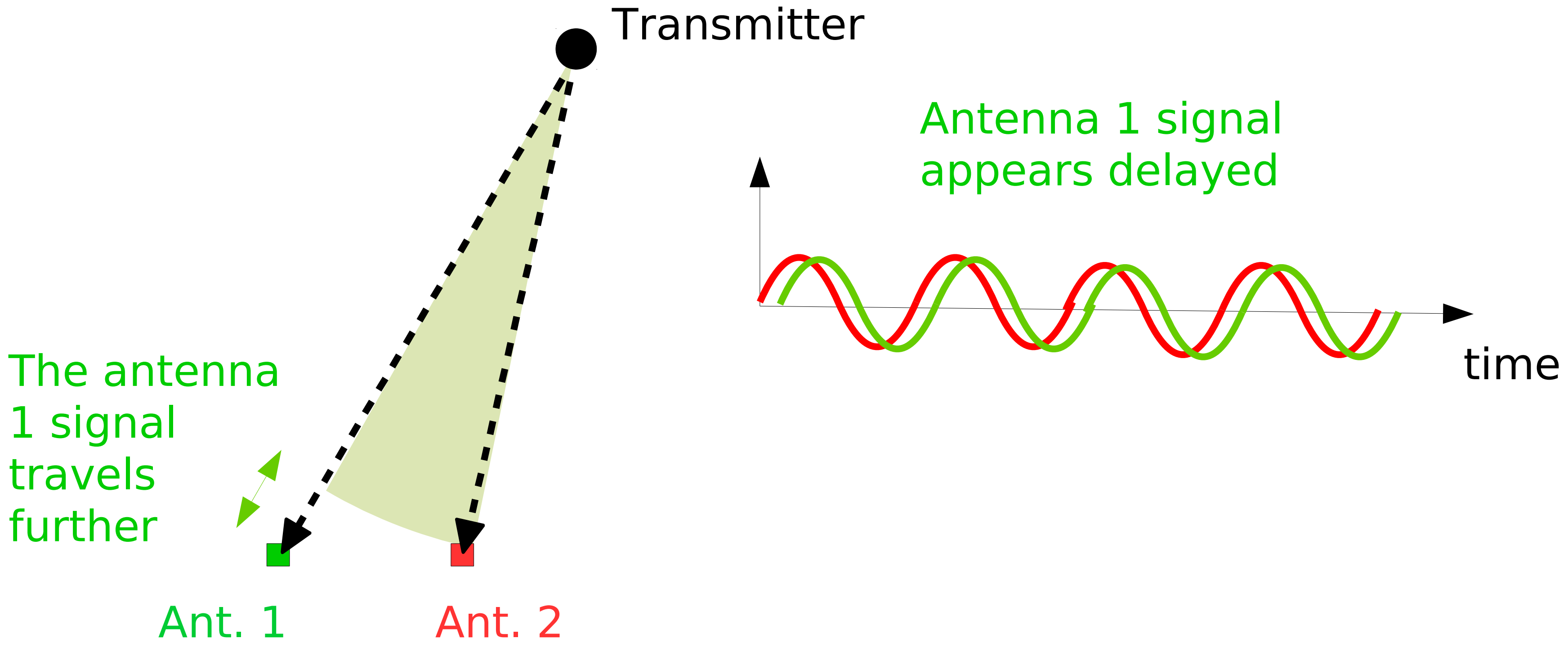

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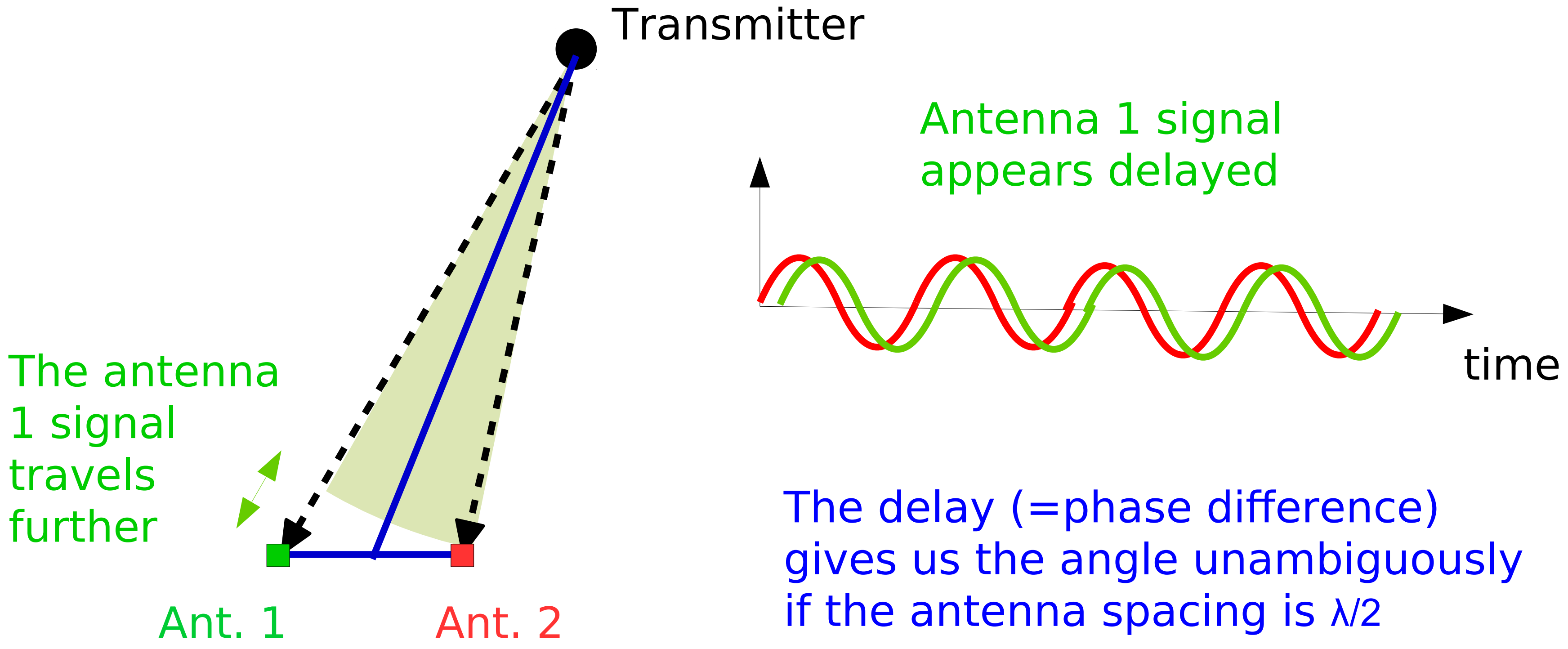
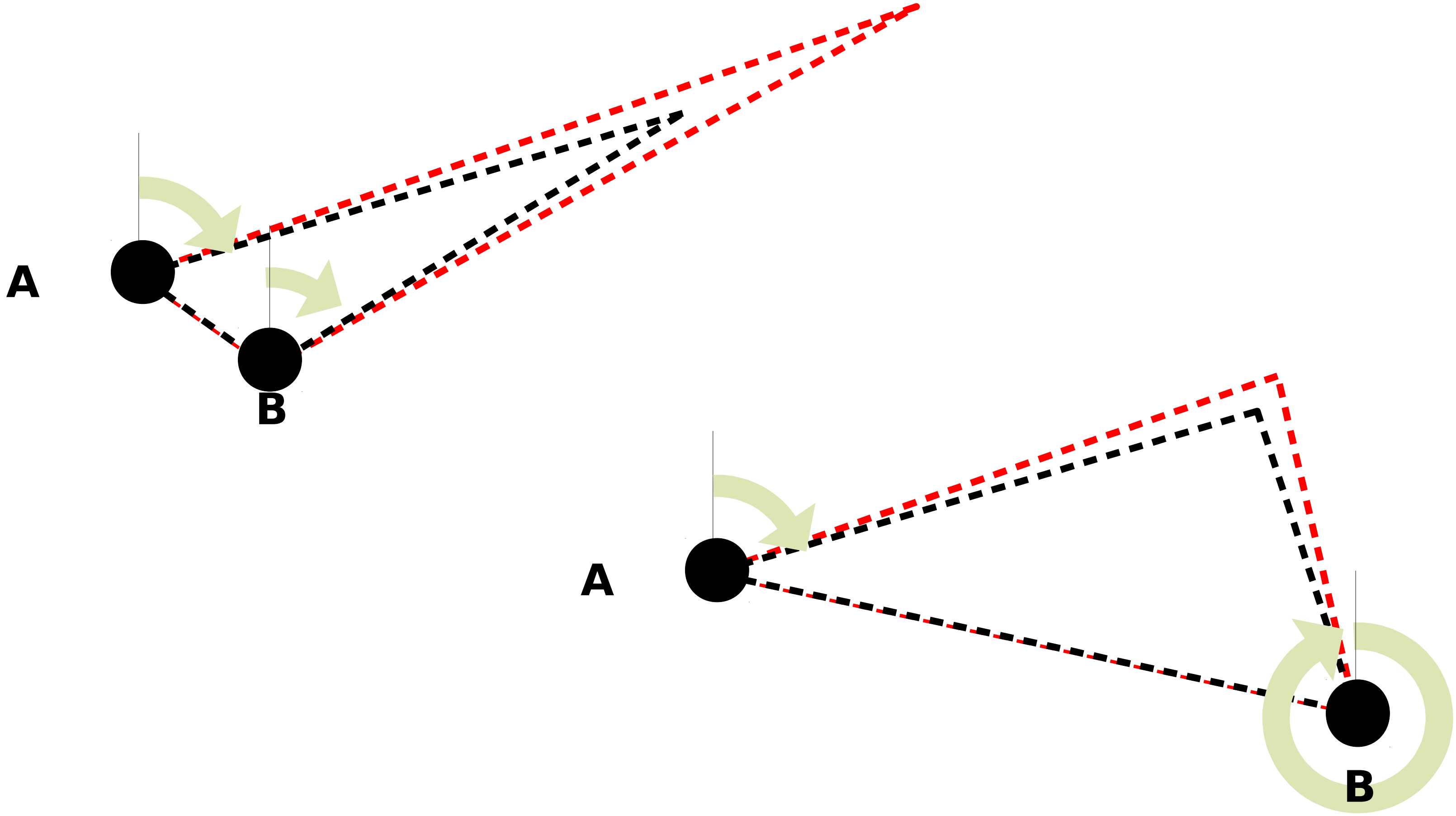
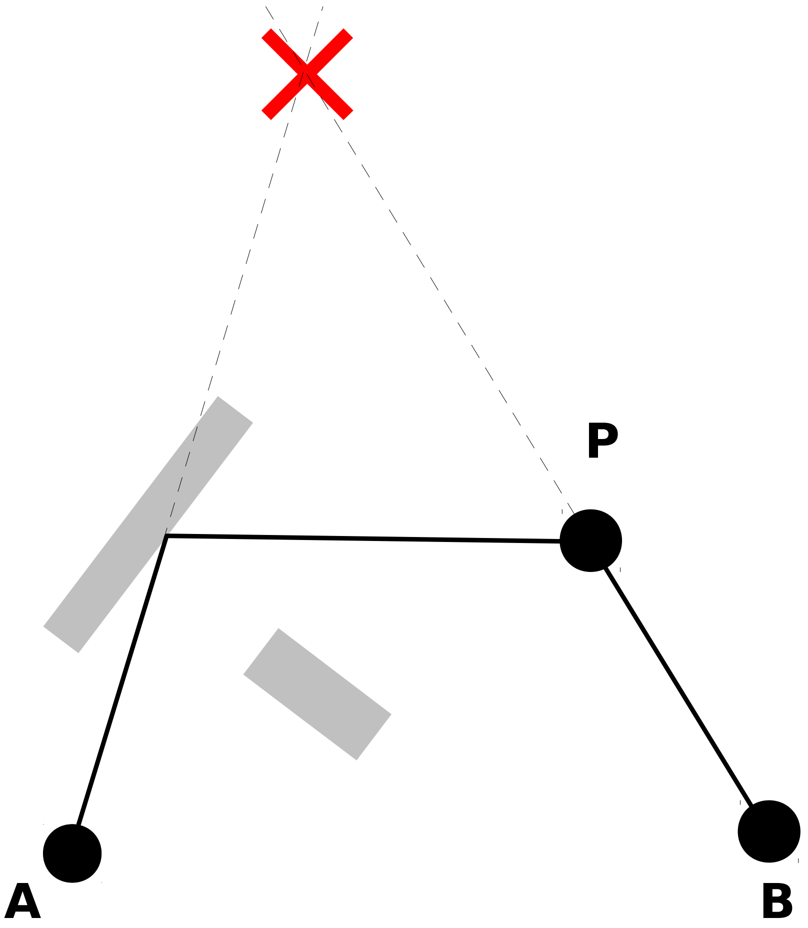


The delay (=phase difference) gives us the angle unambiguously if the antenna spacing is $\lambda/2$

Geometry is Important



But Multipath still a Killer

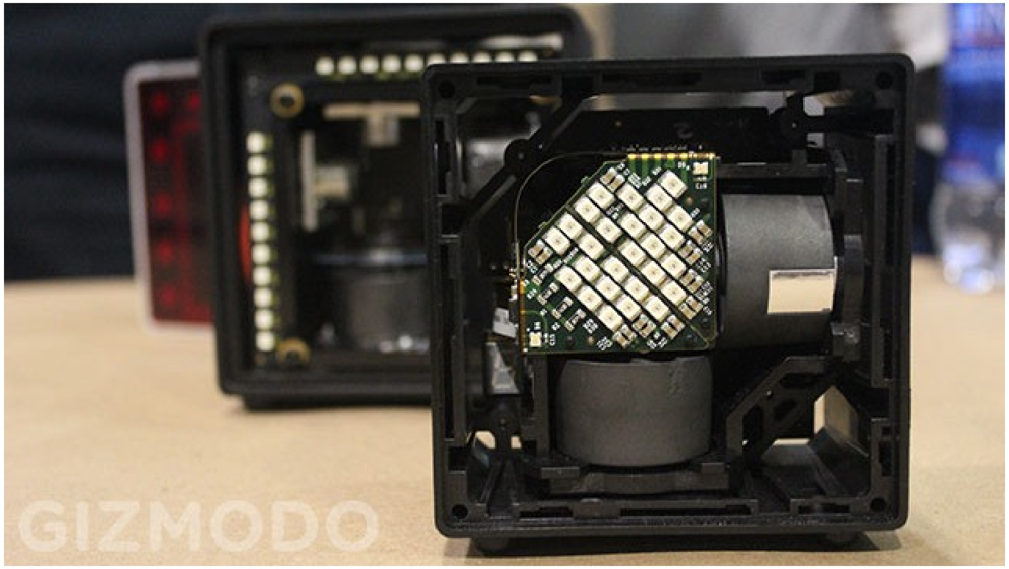


Optical: Valve's neat solution for VR

This Is How Valve's Amazing Lighthouse Tracking Technology Works

Sean Buckley
5/19/15 12:00pm · Filed to: LIGHTHOUSE

103.7K 294 19



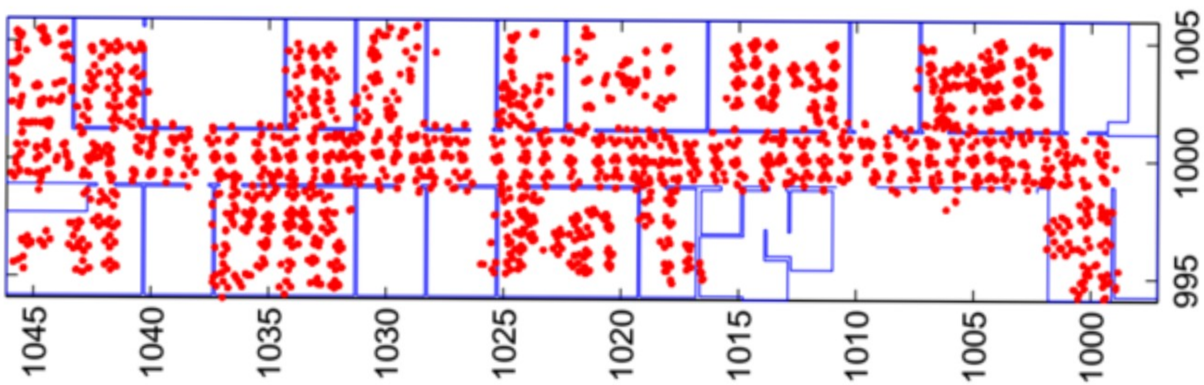
Valve's virtual reality demo at GDC was nothing short of magical—it used fancy emitter technology to let us actually walk around a demo room. It felt so real. Valve calls the tech Lighthouse, and it's kind of genius.

https://gizmodo.com/this-is-how-valve-s-amazing-lighthouse-tracking-technol-1705356768

Indoor Localisation from Pattern Recognition

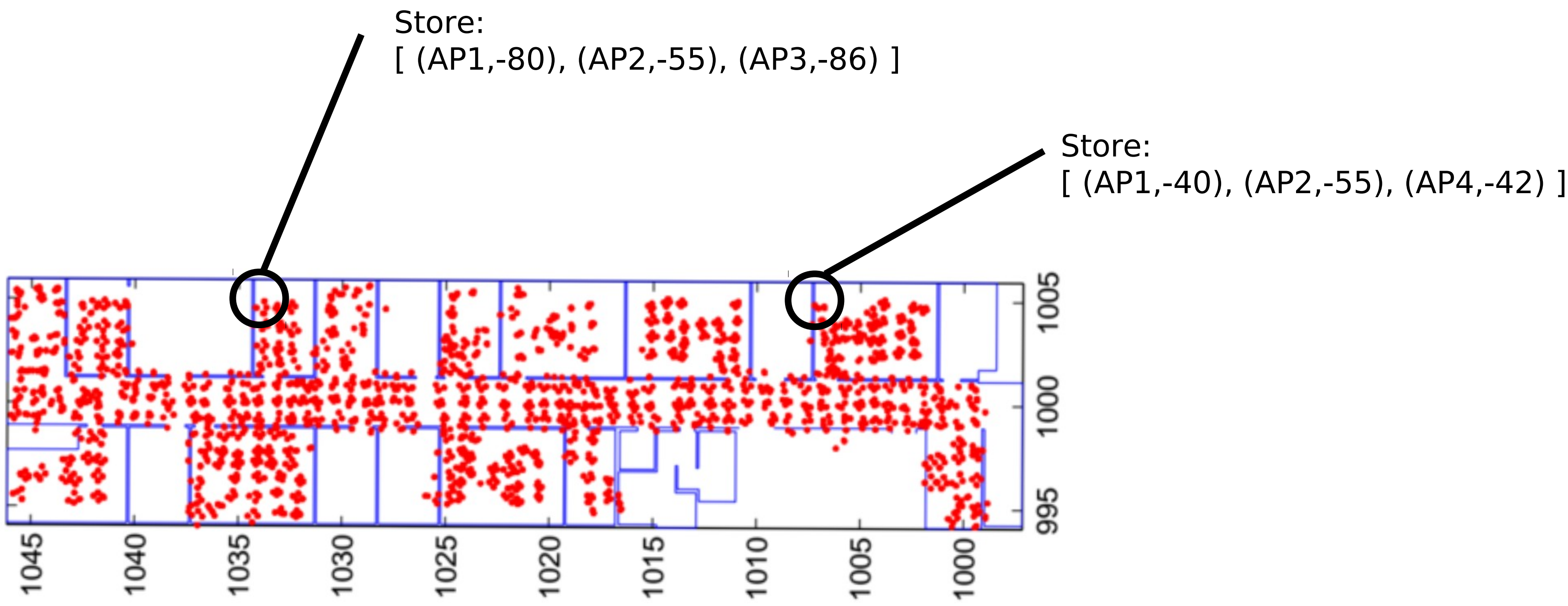
Signal Fingerprinting

- Developed for radio systems, esp. WiFi
- You perform an 'offline' survey, manually measuring signal properties (usually strength) at a range of spatial positions
- → “Signal map” or “fingerprint map”



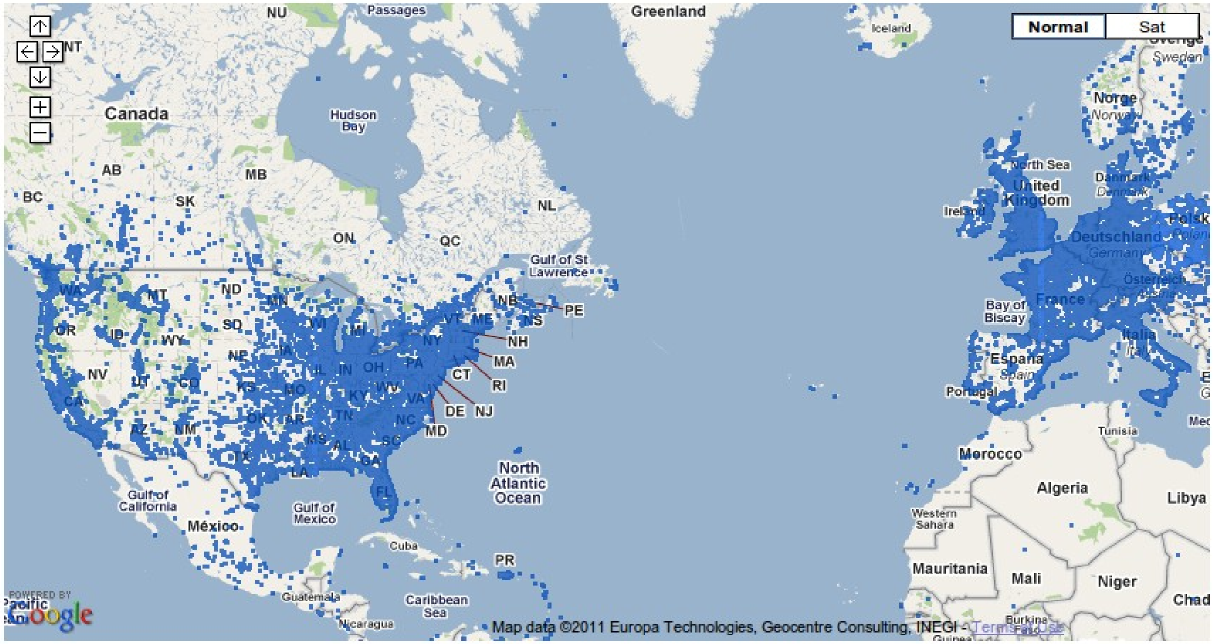
Nearest Neighbour in Signal Space (NNSS)

- Offline ("survey") stage
  - Identify known locations that cover the space comprehensively (how?)
  - At each point take 10 or so WiFi RSSI measurements
  - Average and store



Signal Fingerprinting

- In the online phase, we scan the local signals and perform some form of pattern matching to the survey points
- This is essentially indoor wardriving. The outdoor equivalent is well established



Nearest Neighbour in Signal Space (NNSS)

- Online
  - Mobile device scans WiFi and builds a vector of observations **m** (e.g. ((Ap1,-40), (AP2,-60))
  - Now consider every point that we surveyed and find the one "nearest" to the measurement in signal space
    - *Nearest* requires some notion of distance: obvious choice is euclidean distance but other options are possible

$$D^i_{euclidean} = \sqrt{\sum_{j=0}^{A} |m_j - \hat{s}^i_j|^2}$$

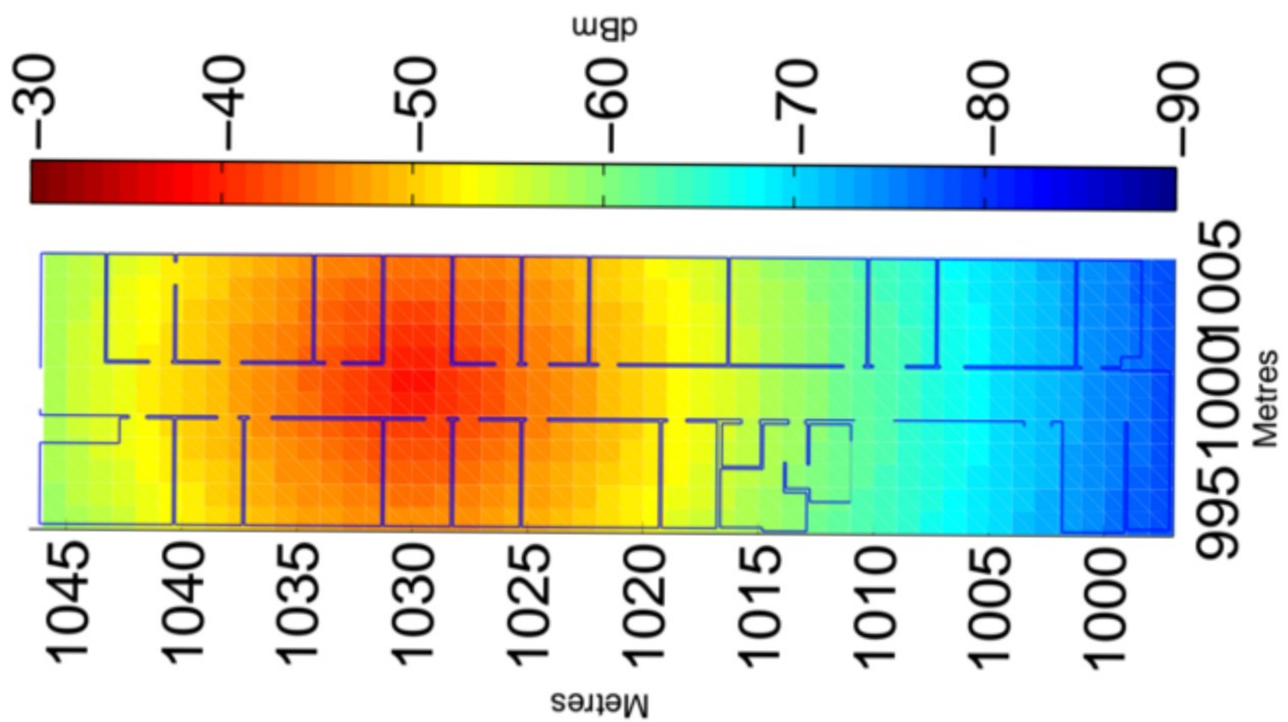
  - Return the position associated with *min*($D_{euclidean}$)
  - Can easily upgrade to kNN (usually k=3 or 4)

Missing values

- How do you compare:
  ((AP1,-30), (AP2,-50), (AP3,-95)) and
  ((AP1,-30), (AP2,-50)) ?
- Maybe AP3 died or you happened not to hear it on the scan (-95 is very weak)
- Naive distance metric has AP3 producing an overall distance of 95!
- Easiest trick is to assign all unseen APs the reader sensitivity (lowest value a reader can report). Usually around -100dBm.
- Then ((AP1,-30), (AP2,-50)) becomes ((AP1,-30), (AP2,-50), (AP3,-100)) and the distance is 5 – more reasonable
- Actually a much harder problem when an AP that you should be hearing strongly dies. Plenty of different approaches but all have nasty corner cases.

Signal Fingerprinting

- We can optionally use regression algorithms to create a continuous map for each base station



The good...

- You're re-using signals that already exist so no need to deploy any hardware!
  - “Opportunistic positioning“
- But the reality is...

...the bad

- APs are deployed for comms, not positioning (→ lower density, poor geometry)
- Body shadowing (we're bags of water that absorb 2.4GHz quite well)
- Environments change so radio paths change
- How do you know where you are when you survey? (you need an indoor positioning system..!)
- Device heterogeneity
- Scanning costs are high on the mobile end – disrupts normal behaviour
- Room ambiguity

Summary

- Location is an important contextual hint
- We have lots of tools to get location, but indoors there are many challenges
- We will also look at a sensor fusion approach for location using wearables in the next lecture