Navigation and Positioning in the 21st Century

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BAE Systems Advanced Technology Centre

Overview

- Why navigation is so important
- Why GPS changed the world
- Why GPS isn’t enough
- Alternative methods of navigation
- Opportunistic positioning
- The Kalman Filter
- Indoor Positioning

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Why is navigation so important?

- The ability to navigate drove animal evolution, by enabling us to
  - Hunt for food
  - Evade predators
  - Find mates
  - Migrate
- We still navigate today for exactly the same reasons!

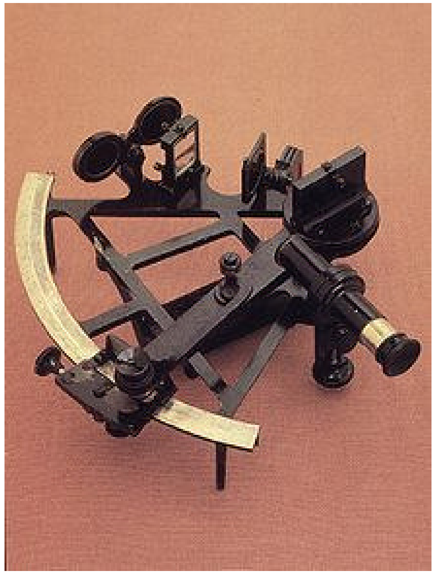
- Most of our senses are used primarily for long and short range navigation (“sense and attack”, or “sense and avoid”)
  - Sight
  - Sound
  - Smell
  - Touch

“Extra Sensory” Navigation Timeline

- 1st Century
  - Chinese discover that “loadstone” points North-South
- 8th Century
  - Chinese magnetise needles to fabricate portable compasses
- 11th Century
  - Viking “sunstones” were used to determine the direction of the sun even under cloudy conditions (exploits birefringence in calcite crystals)

"Extra Sensory" Navigation Timeline

- 15th Century
  - Astrolabes and sextants provide latitude using the elevations of sun or stars
- 18th Century
  - John Harrison creates a chronometer (clock) stable enough to allow longitude to be accurately determined



“Extra Sensory” Navigation Timeline

- 1930s
  - The beginnings of radio positioning, with huge advances during WWII
- 1957
  - Artificial satellites pave the way for satellite based, global positioning systems

GEE – THE AIRCRAFT COMPONENTS

These are the three major components of the GEE system fitted to the bomber aircraft.

The major advantages of the system were that the aircraft did not have to transmit to use it and that any number of aircraft could use the system at the same time.

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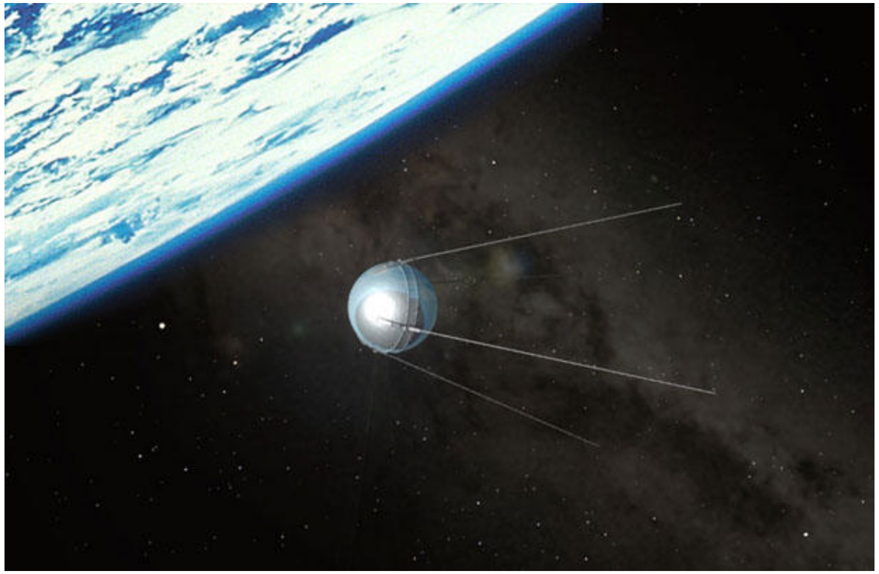
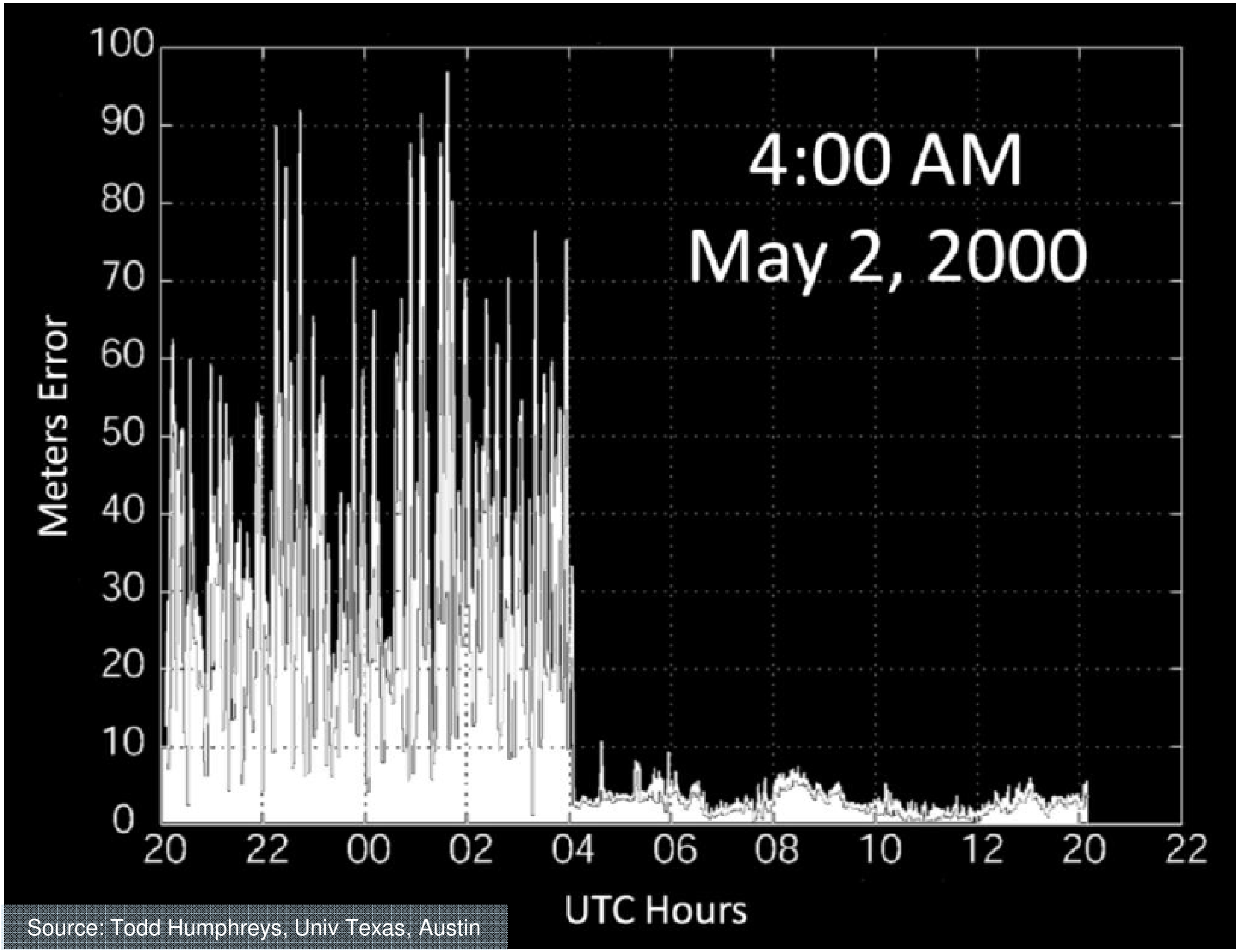


The day the world changed – 2nd May 2000



Source: Todd Humphreys, Univ Texas, Austin

The impact of GPS on society

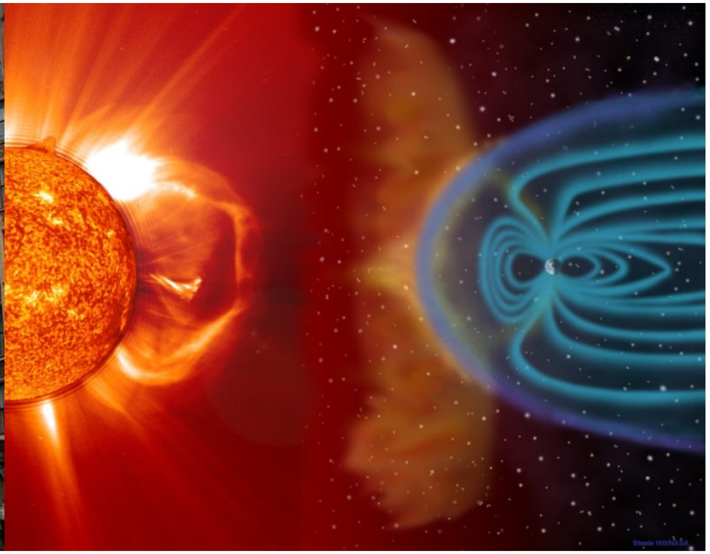
- European Commission estimates that 800 BILLION EURO of the European Economy depends on GPS

- We need it for our
  - Telecommunications and Data Transfer
  - Banking
  - Agriculture
  - Shipping and Air Traffic Control
  - Rail and Road Transport Sector
  - Emergency Services

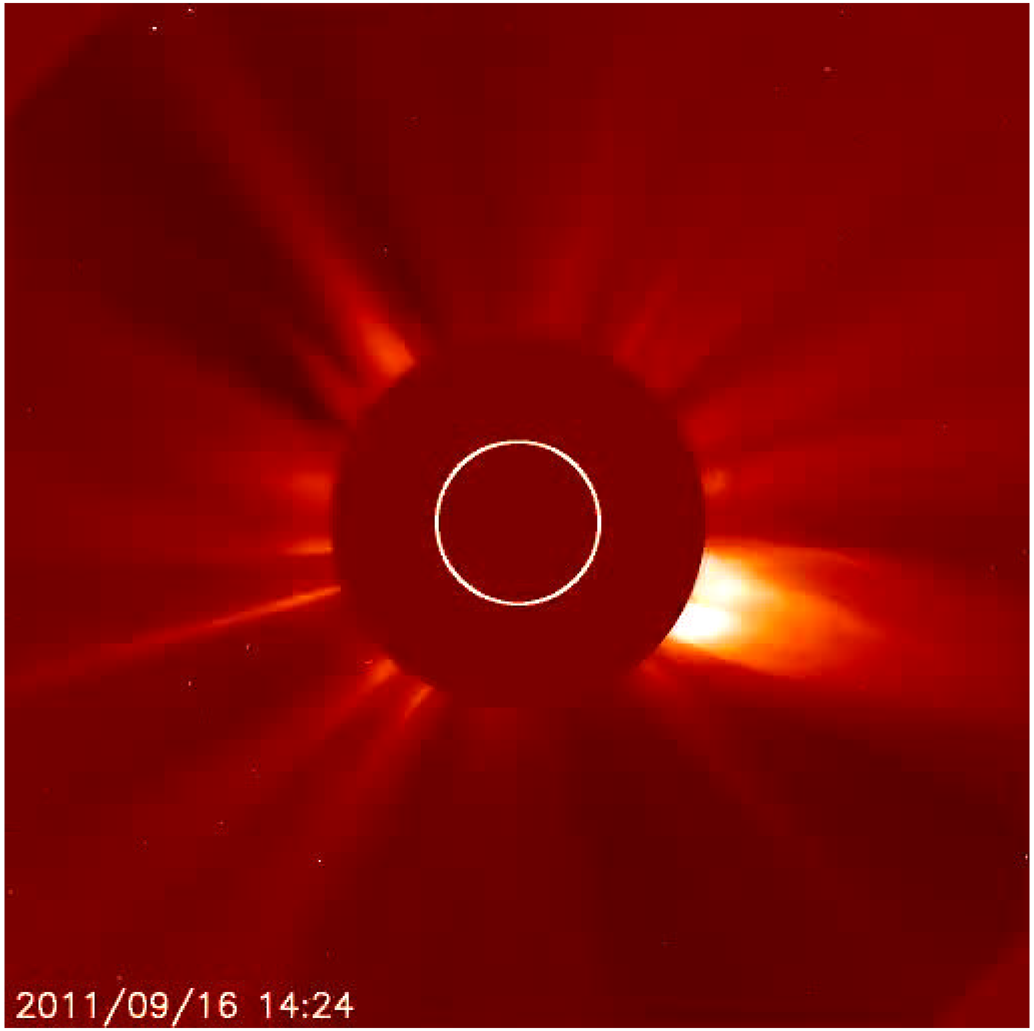
- Today there are multiple Global Navigation Satellite Systems (GNSS)
  - GPS (USA), GLONASS (Russia), Beidou/Compass (China), Galileo (EU)

Why is GPS not enough?

- The very weak signals (a *quadrillionth* of a Watt at the Earth’s surface) can be affected by:
    - Foliage, buildings, power lines, tunnels, etc
    - Electronic interference – malicious or otherwise
    - Space weather, especially during Solar maxima (e.g. 2013)



Coronal Mass Ejections 16/9/11 – 20/9/11



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Aurora Australis

Alternative methods of navigation

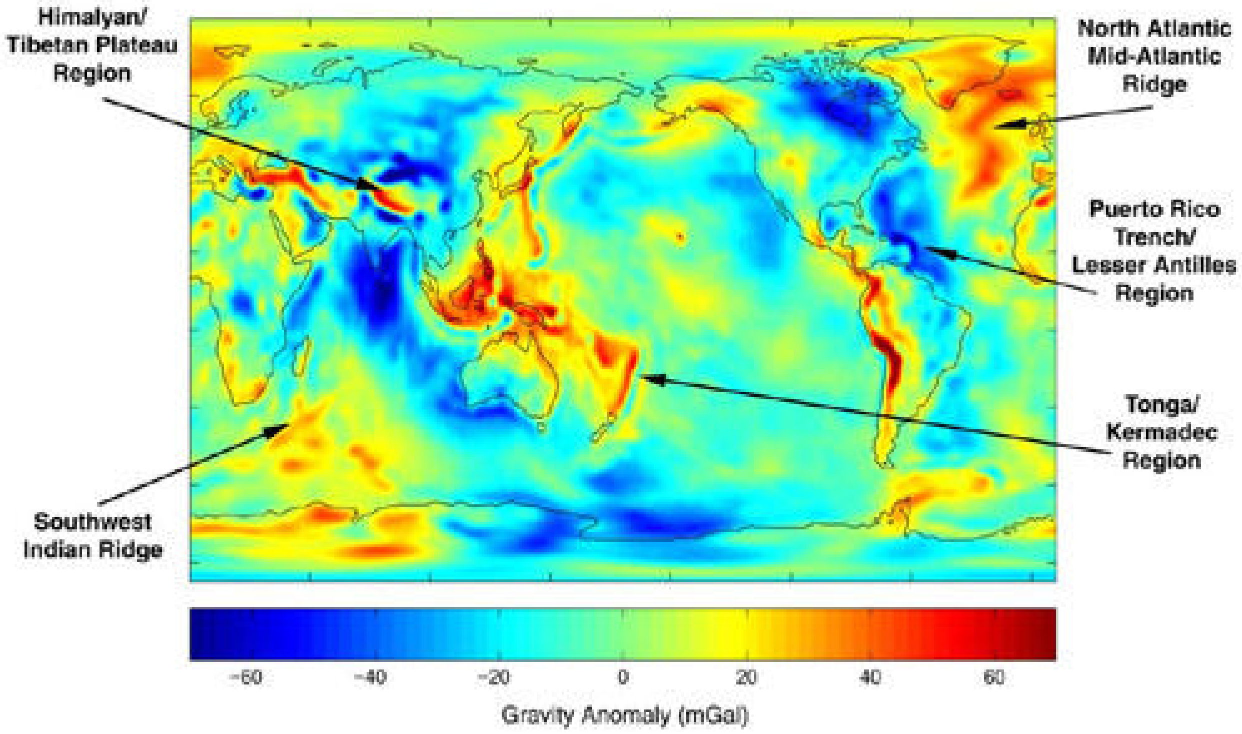
- Stars and other celestial bodies
- Landmarks
- Magnetic field
- Gravitational field
- Scent
- Weather
- Dead reckoning and inertial navigation
- Sound
- Radio Navigation aids

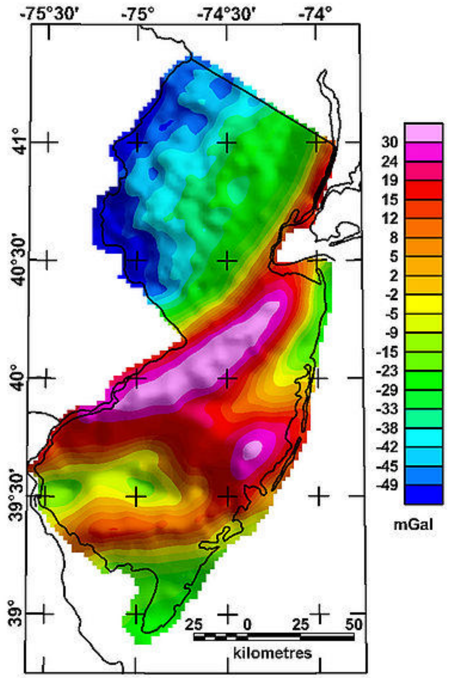
Alternative methods of navigation - Vision

- Stellar cameras
  - Positioning accurate to ~100 metres, precise orientation measurement
    - Requires a stable platform, visibility
- Recognise landmarks and determine relative position
  - Requires databases, significant processing, visibility, etc.
- Visual Odometry
  - Use cameras to infer motion (determine velocity and changes in heading)

Alternative methods of navigation

- Map matching
  - Gravitational/magnetic/photographic/radar/sonar/radio
    - Requires stable maps (slow temporal changes), databases, etc





Gravitational Aiding of an Inertial Navigation System

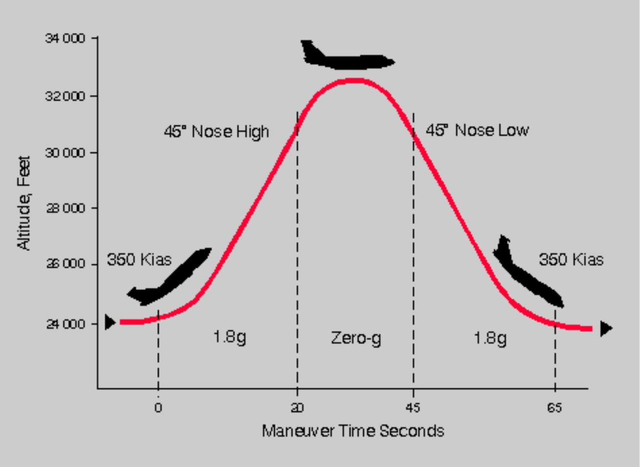
- What is an Inertial Navigation System?
    - Integrate the outputs from accelerometers and gyroscopes over time to determine changes in orientation, velocity, and position
    - Accuracy degrades exponentially with time (integration of errors)

- Gyroscopes
    - Determine orientation changes

- Accelerometers
    - Determine forces acting on the system
    - Integrate acceleration to determine velocity, integrate velocity to determine position
    - Must account for the effect of gravity

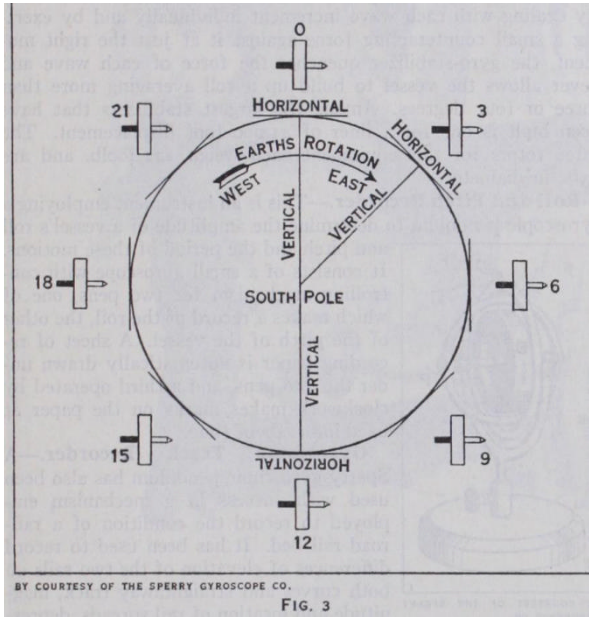
Gravitational Aiding of an Inertial Navigation System

- Effect of gravity on an Inertial Navigation System
  - A free-falling accelerometer measures no force (gravity is accelerating all components downwards equally, so no relative measurement between test mass and sensor frame can be made)
  - *An accelerometer is a device that senses deviation from free fall*
  - A dropped INS cannot record it’s motion towards the centre of the Earth unless you <u>add in</u> the force of gravity before integrating



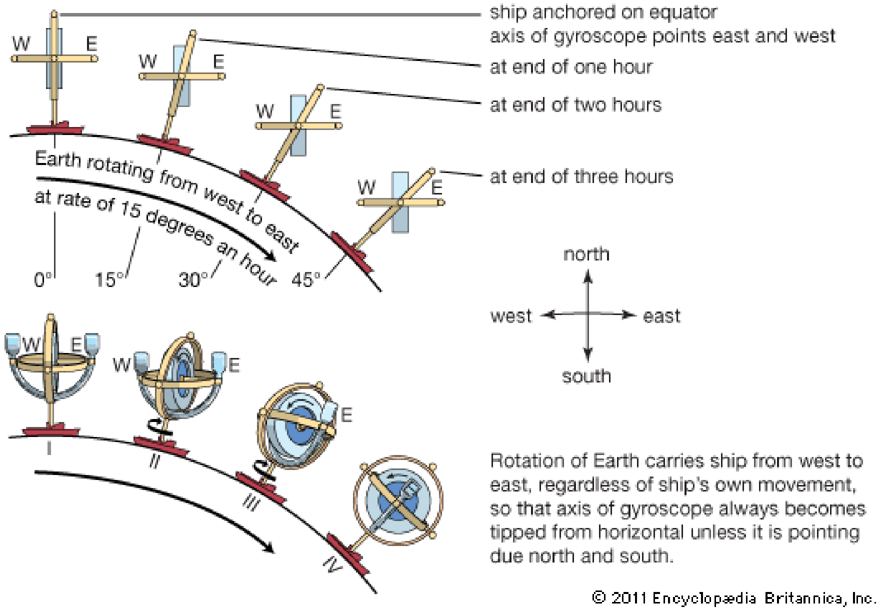
Gravitational Aiding of an Inertial Navigation System

- To add in gravity correctly we need to know which direction is “down”
- Gyroscopes provide orientation relative to the horizon
- However, the rotation of the Earth, and motion over the curved Earth must also be accounted for



BY COURTESY OF THE SPERRY GYROSCOPE CO.

FIG. 3



Rotation of Earth carries ship from west to east, regardless of ship's own movement, so that axis of gyroscope always becomes tipped from horizontal unless it is pointing due north and south.

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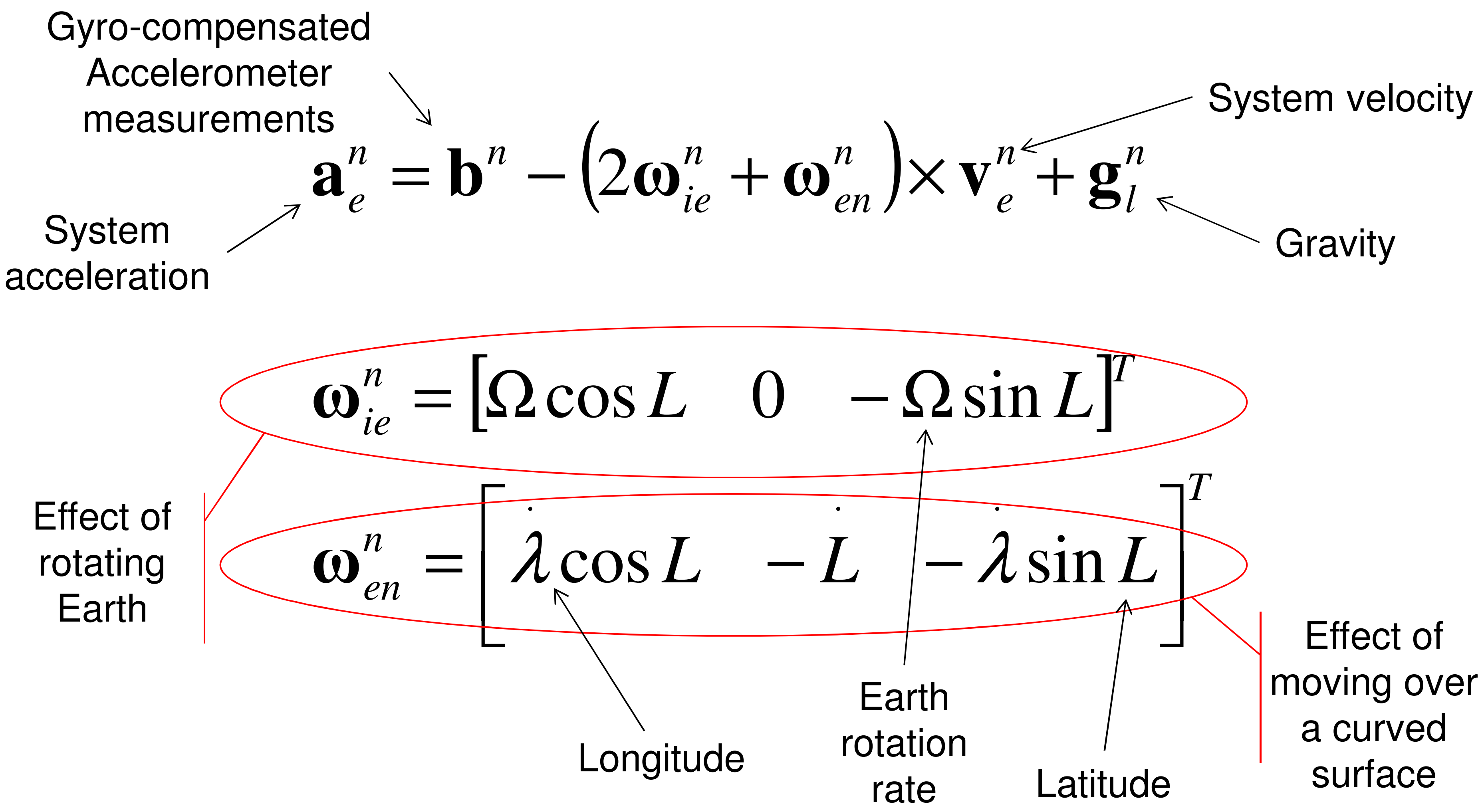
The Navigation Equation



Gyro-compensated Accelerometer measurements

System velocity

$$\mathbf{a}_e^n = \mathbf{b}^n - \left(2\boldsymbol{\omega}_{ie}^n + \boldsymbol{\omega}_{en}^n\right)\times \mathbf{v}_e^n + \mathbf{g}_l^n$$

System acceleration

Gravity

$$\boldsymbol{\omega}_{ie}^n = \left[\Omega\cos L \quad 0 \quad -\Omega\sin L\right]^T$$

Effect of rotating Earth

$$\boldsymbol{\omega}_{en}^n = \left[\dot{\lambda}\cos L \quad -\dot{L} \quad -\dot{\lambda}\sin L\right]^T$$

Effect of moving over a curved surface

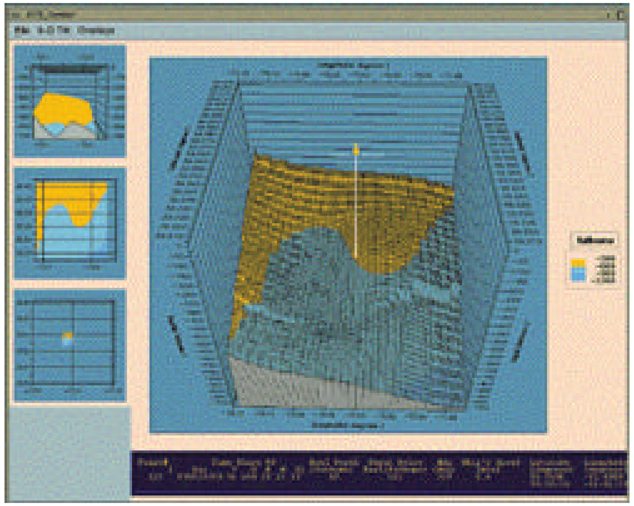
Longitude

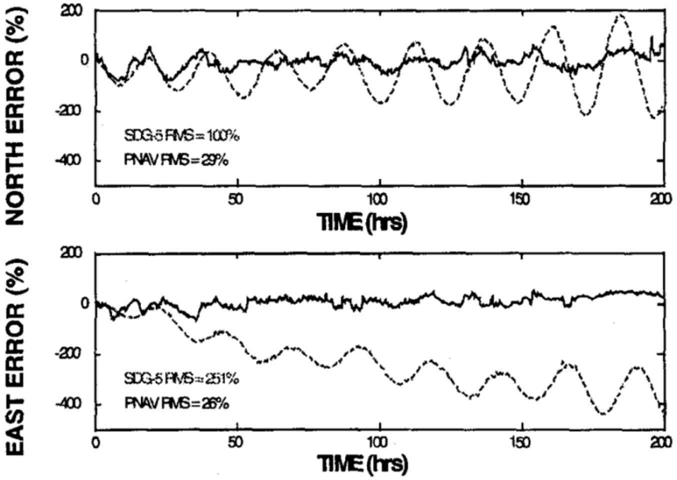
Earth rotation rate

Latitude

Gravitational Aiding of an Inertial Navigation System

- Gravitational gradiometers and gravimeters :
  - Measurements of gravitational strength and gradient
  - Measurements of vertical Coriolis acceleration
  - Measurements of vertical deflection
  - Provision of passive terrain estimation



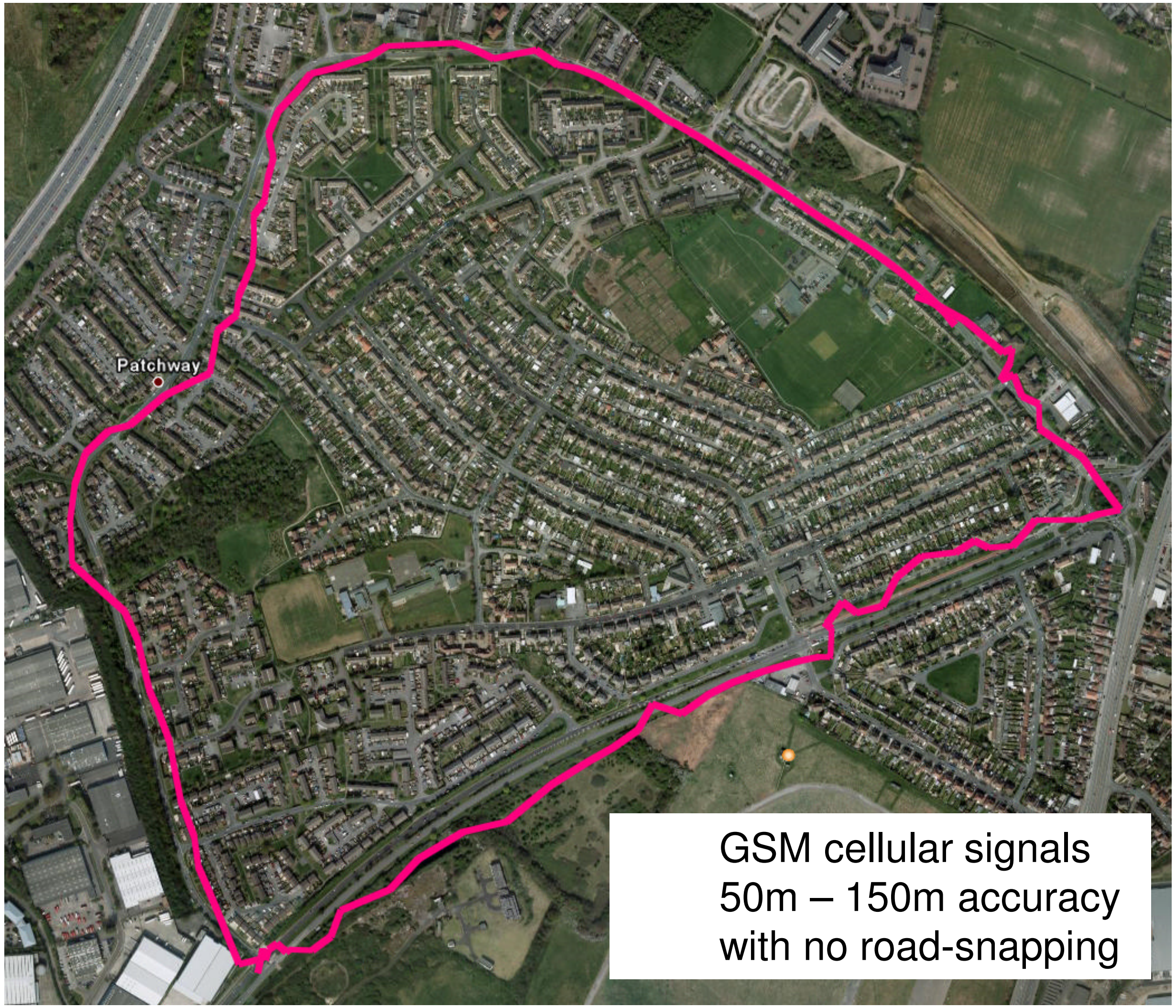


Navigation using Opportunistic Radio Signals

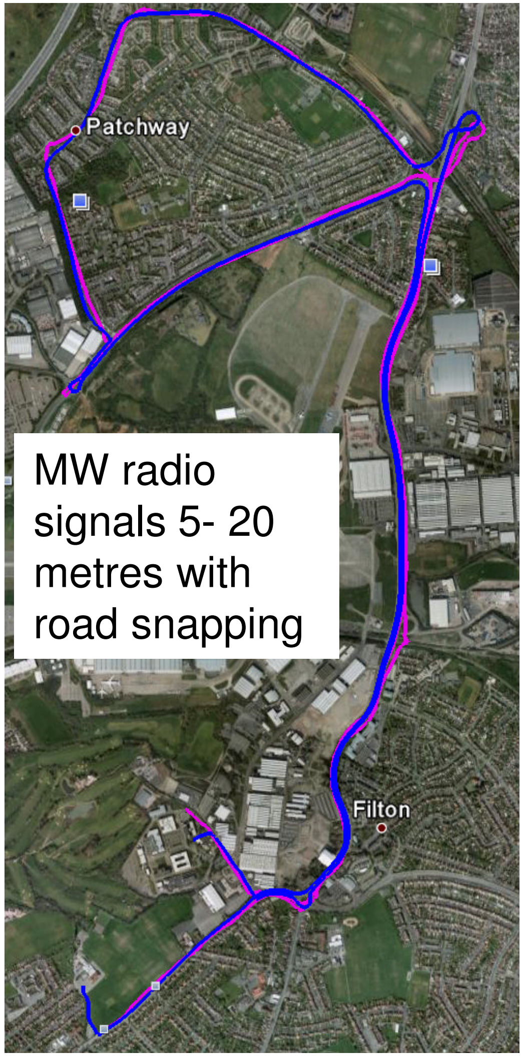
- Advantages
  - High signal availability in populated inland areas
    - 2G cellular, 3G cellular, TV, VHF radio, MW radio, DAB radio, WiFi…
  - Much higher transmission powers than GPS provides better signal penetration
    - GPS = 50W @ 20,200km; Droitwich MW transmitter = 50,000W @ 1-1000km
  - Great range in frequencies (1MHz to 3GHz)
    - Protection against interference
    - Independent propagation characteristics
    - Fusion of multiple signals of different provides integrity monitoring

- Disadvantages
  - The signals are typically not designed for radio positioning
    - Some need a calibration step, and smart navigation filters are required
  - The database of source locations may be unknown
    - Simultaneous Localisation and Mapping allows navigation without prior knowledge of source locations

Navigation using Opportunistic Radio Signals



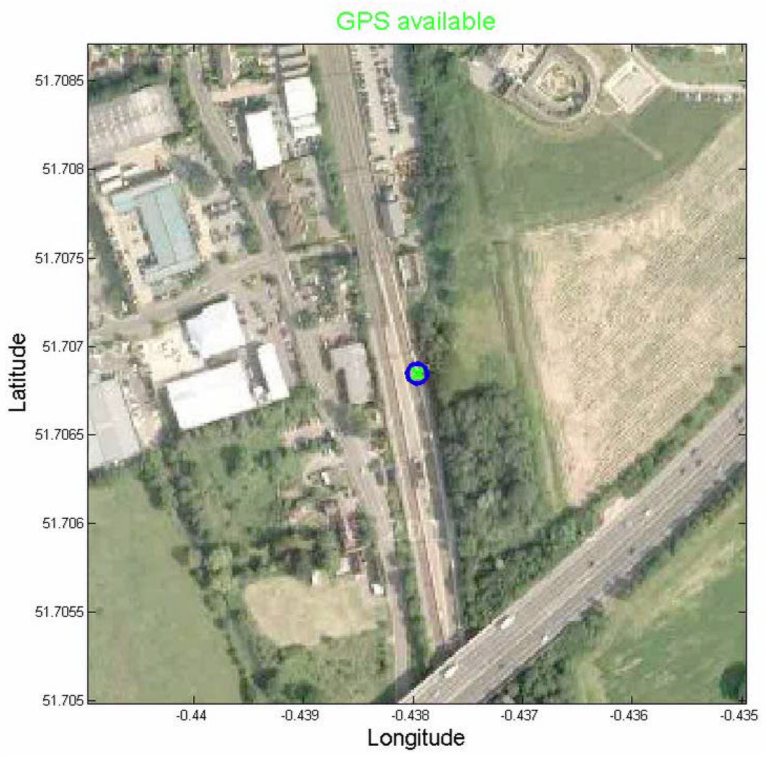
GSM cellular signals
50m – 150m accuracy
with no road-snapping



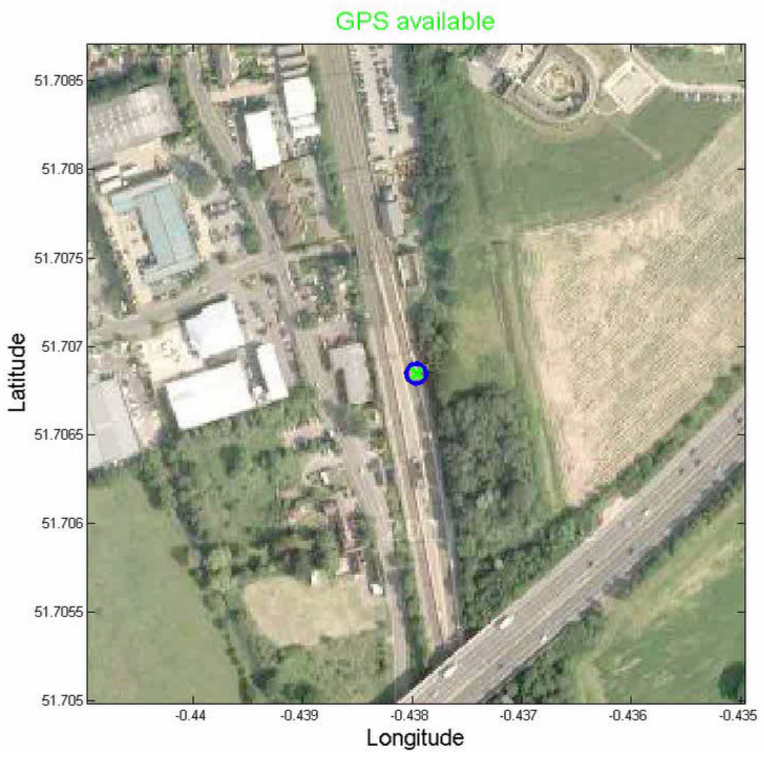
MW radio
signals 5- 20
metres with
road snapping

Supporting rail positioning requirements

Tracking using GSM-R with rail snapping



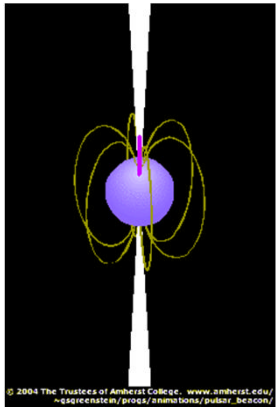
For comparison: Tracking using GSM-R **without** rail snapping

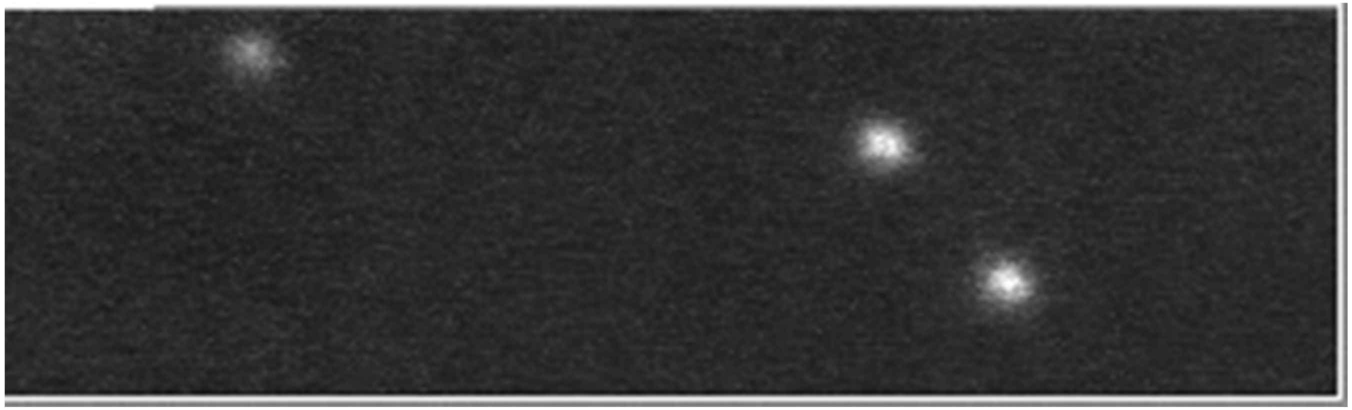


Provides 6m accuracy @ 66% confidence,
12m accuracy @ 95% confidence

Astronomical opportunistic radio positioning

- Utilizing the predictability and stability of Pulsars to navigate in deep space
- A Pulsar is a rotating Neutron Star emitting pulses of EM radiation
  - Matter falling onto the Neutron Star is accelerated through curved paths by the star's powerful magnetic field
  - EM radiation is "beamed" out from the magnetic poles of the stars





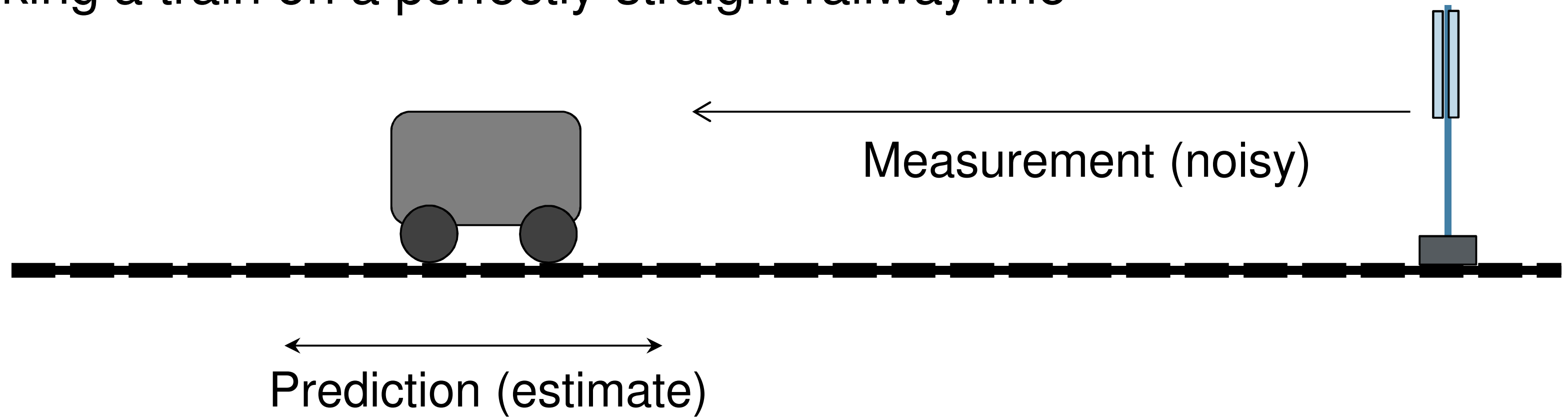
- NASA and ESA are both investigating the use of pulsar navigation to support deep space missions

Fusing data – the Kalman Filter

- The most famous navigation filter – (Rudolph Kalman, 1960)
  - A navigation filter fuses *predictions* based on models or estimates of allowed user movement and *measurements* from available sensors
  - The Kalman filter took Armstrong to the moon – and prevented him from smashing into it!
    - You own at least one Kalman Filter yourself, probably many more.
    - GPS receivers, phase-locked loops in electronic devices, computer games (software and hardware)…

Simple 1-Dimensional navigation problem

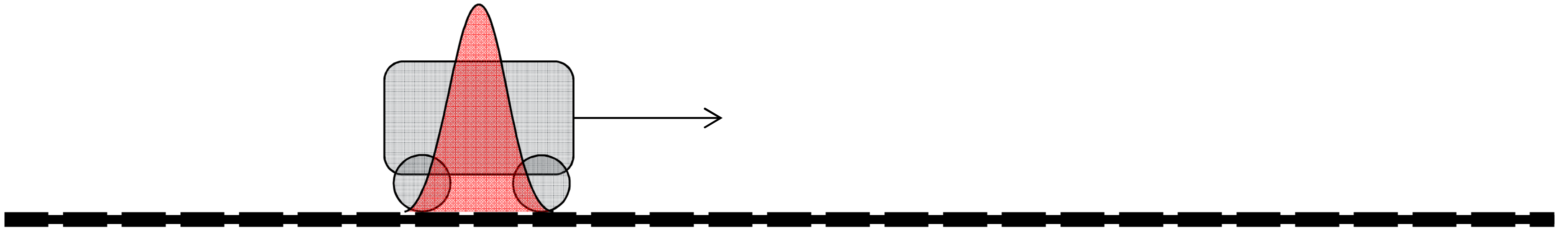
- Tracking a train on a perfectly-straight railway line



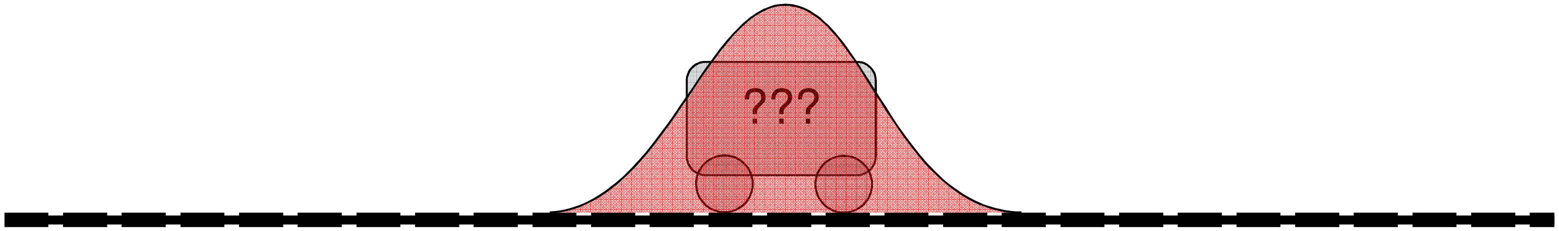
- Estimate change in position of train using control inputs (if available) or simple knowledge (maximum acceleration and deceleration possible, etc)
- Fuse this estimate with the available sensor measurements (in this case a radio ranging measurement) and determine optimum estimate given all available information

Probability framework

- Take last known state of train (position, velocity, braking force, etc)



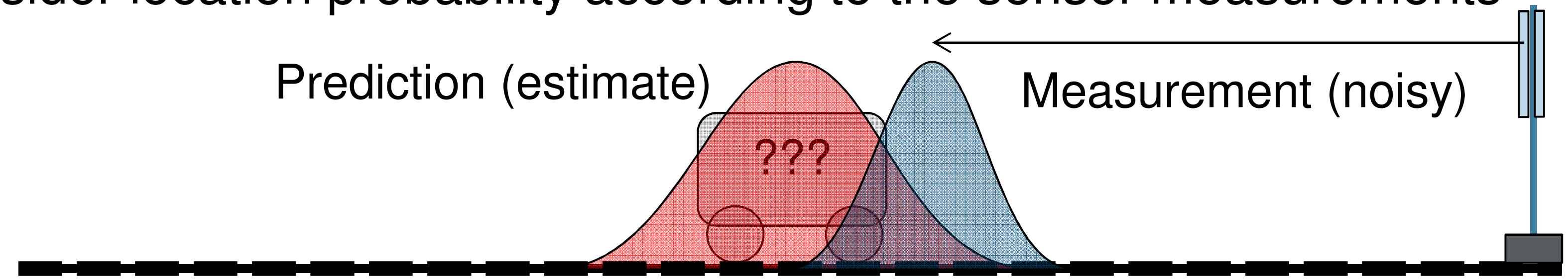
- Make a prediction of where the train is now, accounting that it may have braked or accelerated in the intervening period



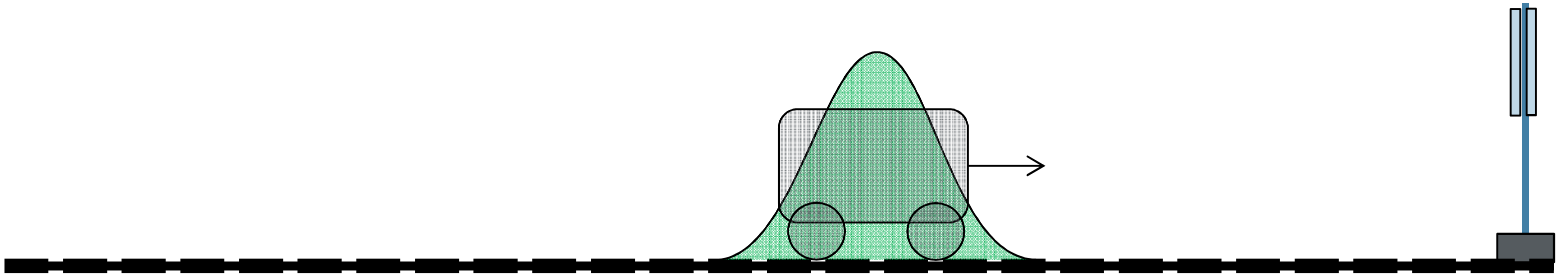
Prediction (estimate)

Probability framework

- Consider location probability according to the sensor measurements



- Combine probability density functions to provide optimal estimate



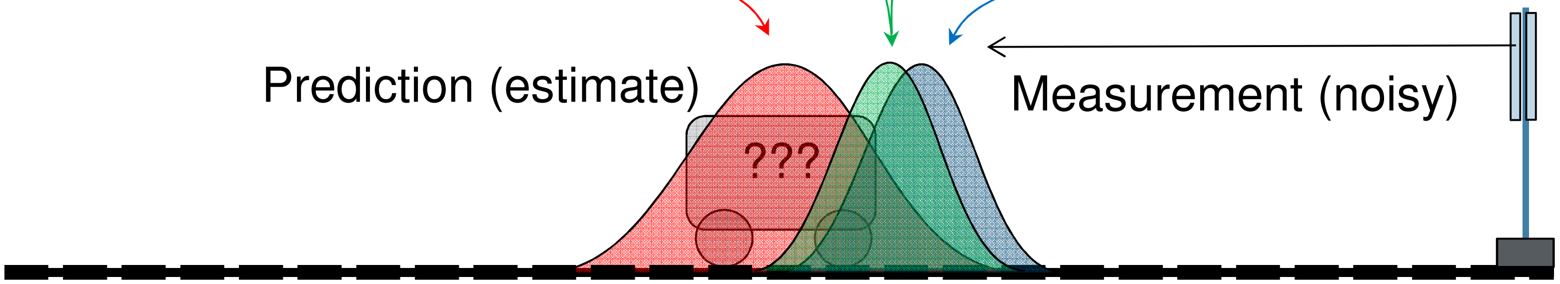
Fused estimate

Deriving Kalman's Filter as the product of two Gaussians

$$x_1(r) \triangleq \frac{1}{\sqrt{2\pi\sigma_1^2}} e^{-\frac{(r-\mu_1)^2}{2\sigma_1^2}} \qquad x_2(r) \triangleq \frac{1}{\sqrt{2\pi\sigma_2^2}} e^{-\frac{(r-\mu_2)^2}{2\sigma_2^2}}$$

Mean and variance of the new Gaussian given by the product of x_1 and x_2

$$\mu = \frac{\mu_1\sigma_2^2+\mu_2\sigma_1^2}{\sigma_1^2+\sigma_2^2} \qquad \sigma^2 = \frac{\sigma_1^2\sigma_2^2}{\sigma_1^2+\sigma_2^2}$$



Prediction (estimate)

Measurement (noisy)

Deriving Kalman's Filter as the product of two Gaussians

$$x_1(r) \triangleq \frac{1}{\sqrt{2\pi\sigma_1^2}} e^{-\frac{(r-\mu_1)^2}{2\sigma_1^2}} \qquad x_2(r) \triangleq \frac{1}{\sqrt{2\pi\sigma_2^2}} e^{-\frac{(r-\mu_2)^2}{2\sigma_2^2}}$$

Mean and variance of the new Gaussian given by the product of x_1 and x_2

$$\mu = \frac{\mu_1\sigma_2^2 + \mu_2\sigma_1^2}{\sigma_1^2 + \sigma_2^2} \qquad \sigma^2 = \frac{\sigma_1^2\sigma_2^2}{\sigma_1^2 + \sigma_2^2}$$

$$\mu = \mu_1 + \frac{\sigma_1^2(\mu_2 - \mu_1)}{\sigma_1^2 + \sigma_2^2} \qquad \sigma^2 = \sigma_1^2 - \frac{\sigma_1^2\sigma_1^2}{\sigma_1^2 + \sigma_2^2}$$

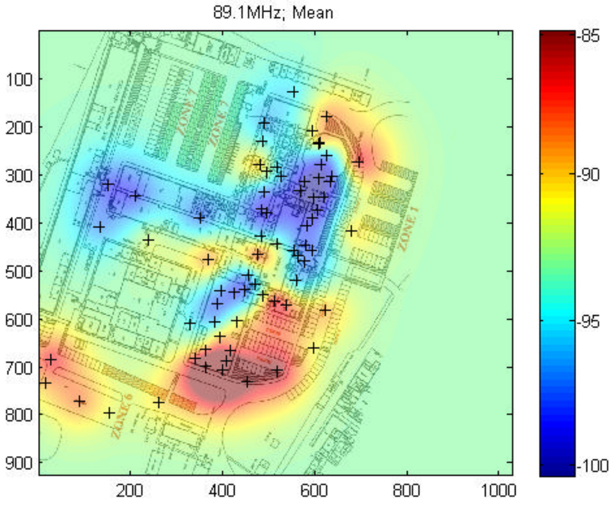
$$\hat{\mathbf{y}}_{\mathbf{k|k}} = \hat{\mathbf{y}}_{\mathbf{k|k-1}} + \mathbf{K_k j_k} \qquad \mathbf{P_{k|k}} = \mathbf{P_{k|k-1}} - \mathbf{K_k H_k P_{k|k-1}}$$

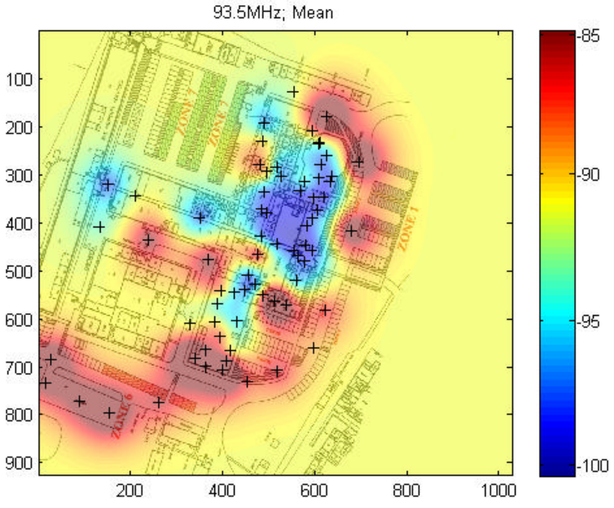
$$\mathbf{K_k} = \mathbf{P_{k|k-1} H_k^T \left(H_k P_{k|k-1} H_k^T + R_k\right)^{-1}} \qquad \mathbf{j_k} = \mathbf{z_k} - \mathbf{H_k} \hat{\mathbf{y}}_{\mathbf{k|k-1}}$$

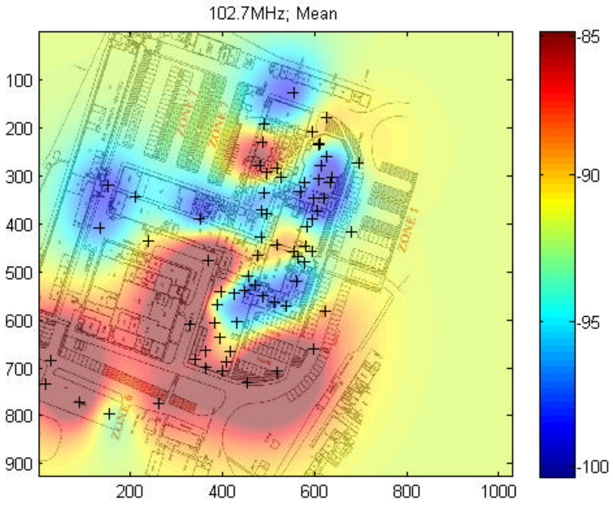
A new take on radio positioning

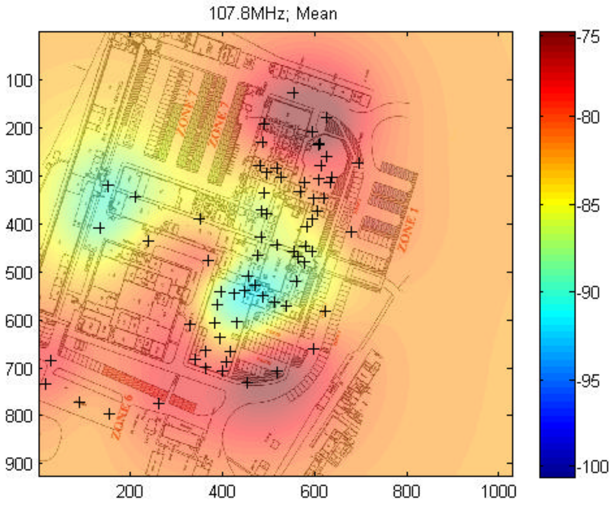
- Traditionally radio positioning has been “propagation based” – a critical assumption involves associating signal flight times to distances from transmitters
  - In complex signal environments (e.g. indoors) multipath interference corrupts timing measurements and dramatically reduces positioning accuracy
  - There is a great desire for GPS-like positioning indoors (emergency services, lone workers, security, smartphone apps, soldier tracking, etc)
  - The development of a new opportunistic radio positioning system than becomes *more accurate* in a *more complex* signal environment was required
    - Ideally the *complete absence* of a given signal should also provide useful positioning information – impossible for a timing-based system

Radio wallpaper (VHF FM 88 MHz – 108 MHz)

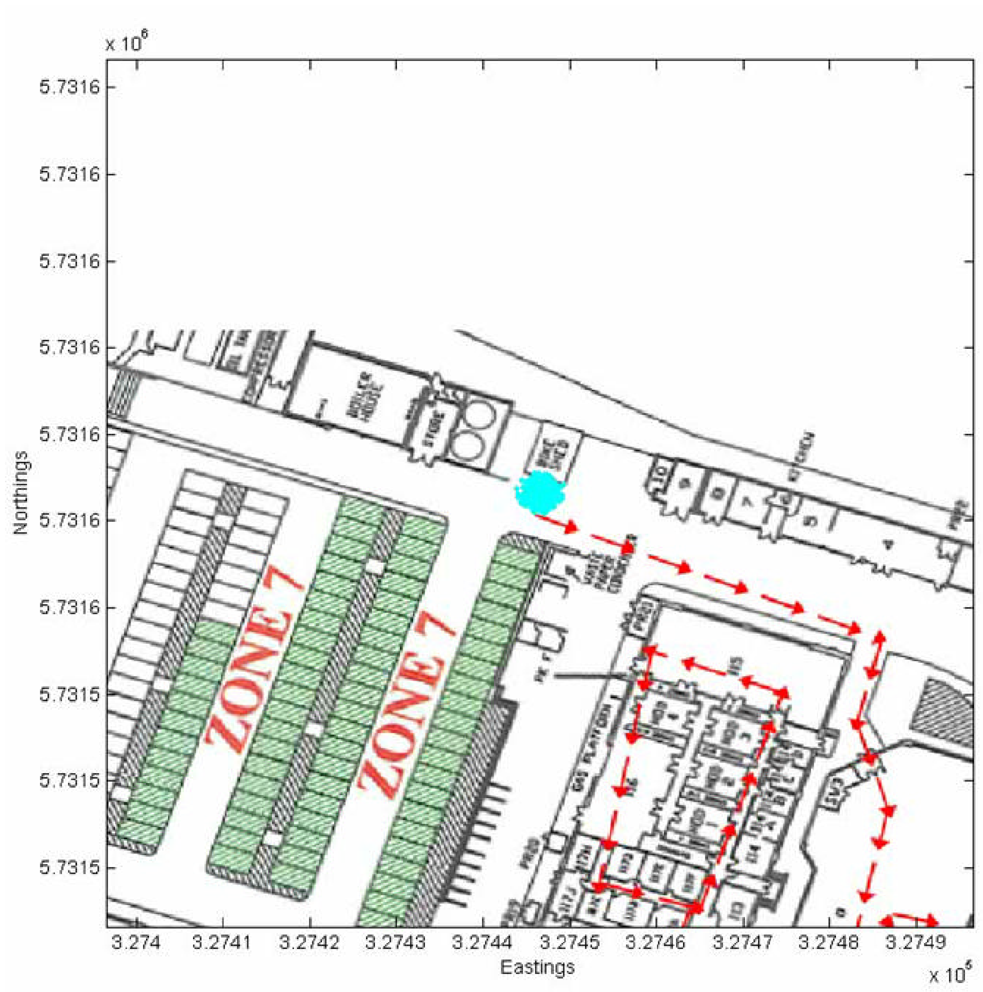








Simultaneous Localisation And Mapping



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- Crash Analysis
- Degaussing
- Direct Write
- Electronics and Packaging
- Engineering Methods for Aerodynamic Characteristic Prediction
- Flight-Qualified Embedded Electronics and Software
- Greenlawn Communications Antenna Systems Laboratory (CASL)
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- Human Performance Modelling
- Hyperspectral Imaging
- Information Processing & Management
- Infrared Signature Modelling and Measurement
- Joint Expeditionary Forensic Facilities (JEFF)
- Laser Surface Treatment of Materials
- Long Range Hyperspectral Imaging System (LORHIS)
- MAGNUM 4Mb Radiation-Hardened SRAM
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- Micro Electromechanical Systems (MEMS)
- Modelling of Composite Damage
- Network Communications and Security
- Optical Asse
- Optical Sign

- Advanced Armor Solutions
- Advanced Waveforms
- AGILE2
- AN/VRC-99x Tactical Communications System
- Beryllium mirrors
- CirCube™
- Communications
- Control & Stabilisation
- Data Forwarding Application
- Design, Process & Product Optimisation
- Electronic Press Kits (EPKs)
- EMMA
- Fibre Optic and Free-space Optical Communications
- File Transfer Application
- Gigabit Data Diode
- Gimbal systems
- Human Factors Integration
- Human Sciences
- Information Assurance
- Information, Networked & Autonomous Systems
- Installed Antenna Modelling
- Joint Tactical Radio System (JTRS)
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- Body-worn electronics
- Computational engineering & fluid dynamics
- Counter IED, detection & neutralisation
- Cyber Security
- Human Sciences
- Impact dynamics modelling and testing
- Less than lethal deterrents
- Micro & nanotechnology and smart materials
- Photonics and laser technologies
- Remote Sensing, radar & antenna development
- Reducing the burden on the dismounted soldier
- Stealth technology and materials
- Technologies for covert & secure operations
- Unmanned and autonomous systems

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