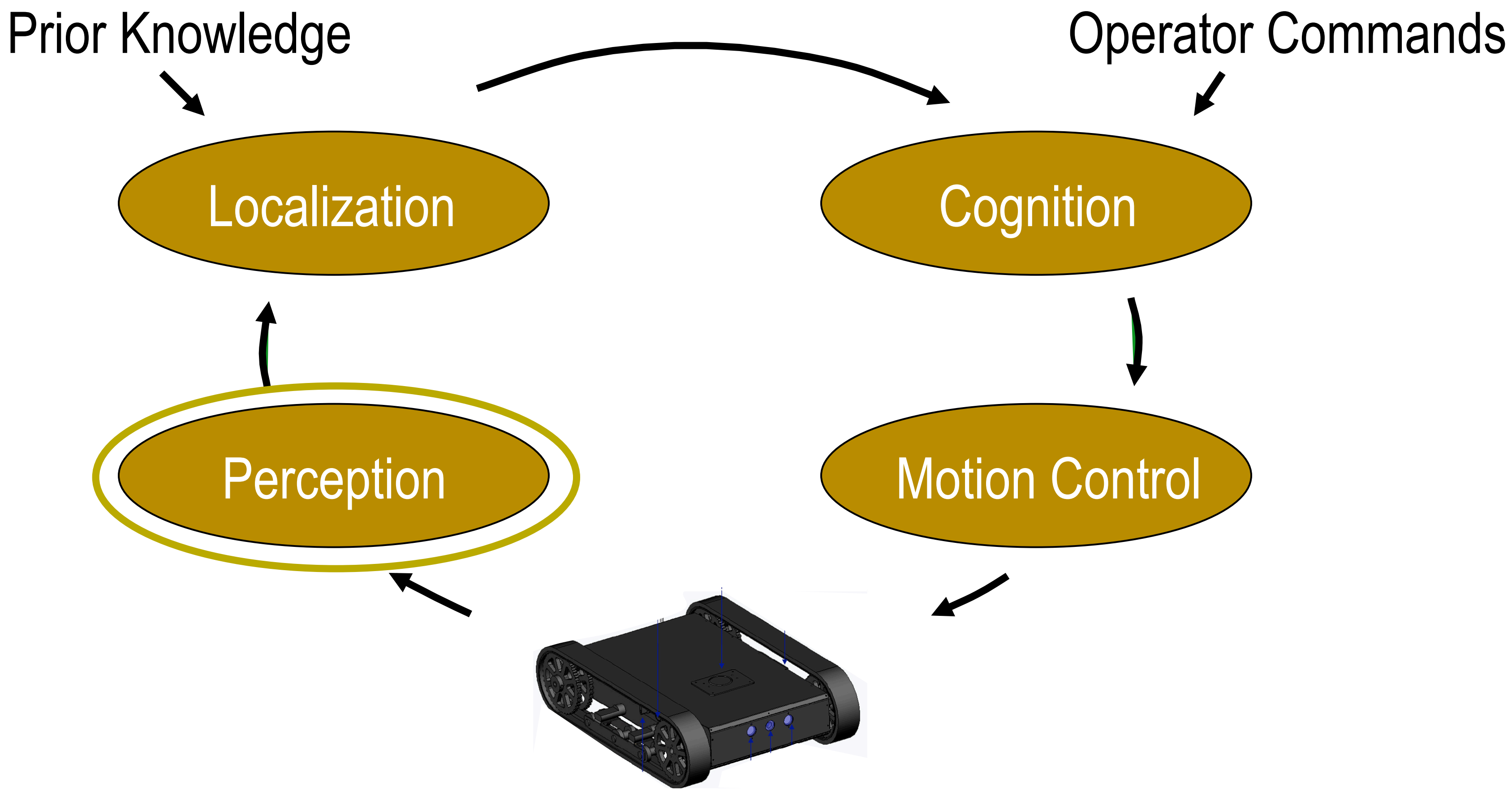
E190Q – Lecture 6
Autonomous Robot Navigation

Instructor: Chris Clark

Semester: Spring 2014

Figures courtesy of Siegwart & Nourbakhsh

Control Structures
Planning Based Control



Sensors II

IMU
Inertial Measurement Unit

Emergency Stop Button

Wheel Encoders

Omnidirectional Camera

Pan-Tilt Camera

Sonar Sensors

Laser Range Scanner

Bumper

Courtesy of Siegwart & Nourbakhsh

Outline – Sensors II

1. Doppler Effect Sensing
2. Beacon Positioning Systems
3. GPS
4. Compass
5. IMU

Doppler Effect Sensing

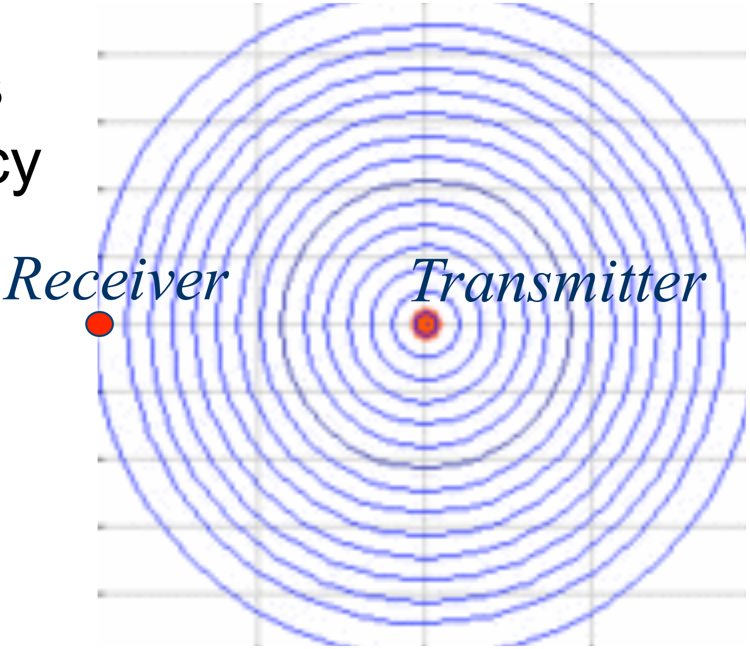
- What is the Doppler effect?

Doppler Effect Sensing

- What is the Doppler effect?

Doppler Effect Sensing

- Stationary transmitter and receiver
  - Receiver detects wave as having the same frequency as the transmitter

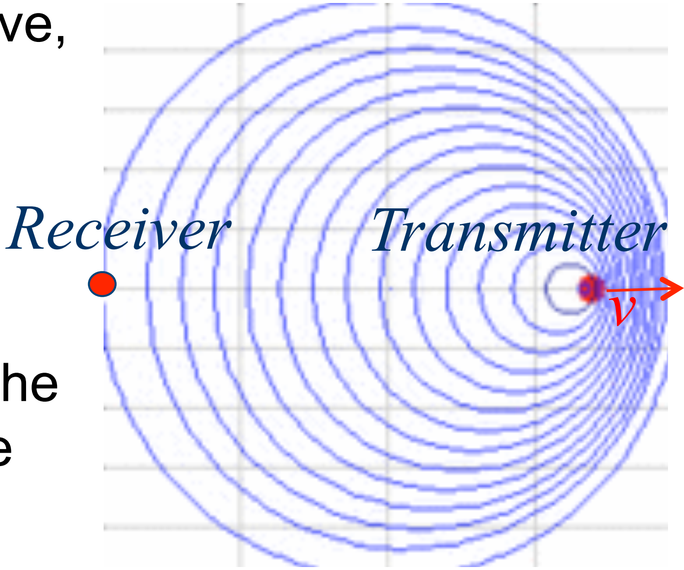


$$f_t = f_r$$

Doppler Effect Sensing

- Tracking moving objects
  - For every period of the transmitted wave, the transmitter moves away from the receiver a distance

$$d = v / f_t$$



  - This lengthens the effective period of the transmitted wave by an amount of time

$$d/c = v/(f_t c)$$

  - So the period of waves at the receiver is

$$1/f_r = 1/f_t + v/(f_t c)$$

Doppler Effect Sensing

- Tracking moving objects
  - Isolating the frequency of the received wave results in

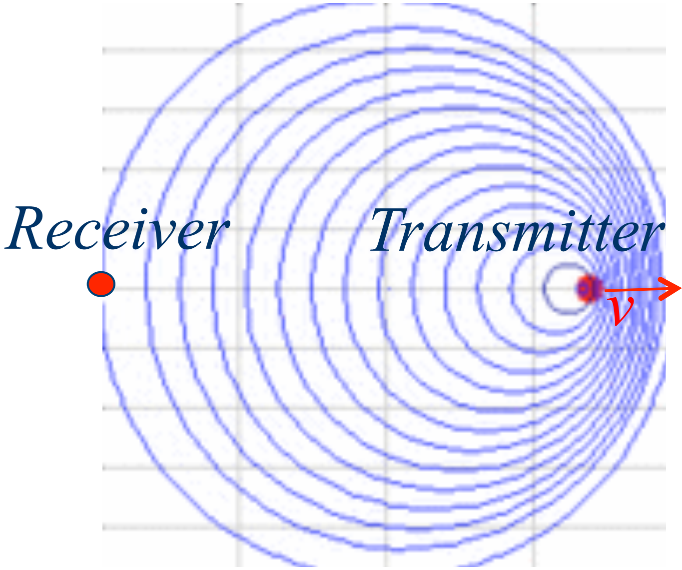
$$f_t = f_r(1 + v/c)$$

  - One can determine the velocity of the transmitter with

$$v = \Delta f\, c \,/\, f_r$$

where the doppler shift is

$$\Delta f = f_t - f_r$$



Doppler Effect Sensing

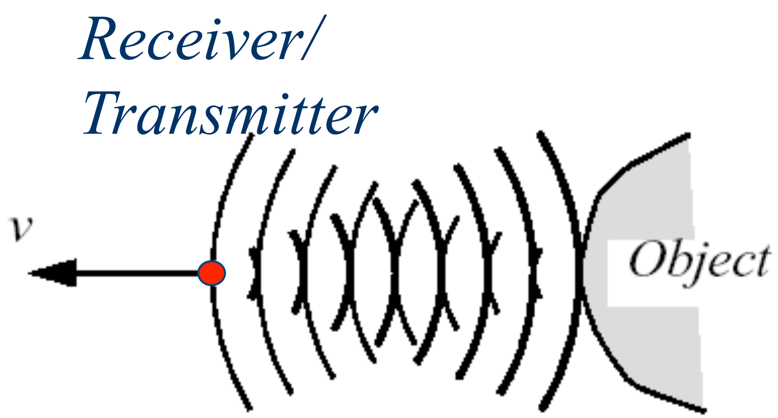
- Tracking moving objects
    - If the receiver is moving

$$v = \Delta f \, c / f_t$$

Doppler Effect Sensing

- Consider a reflected wave
  - The Doppler shift will be doubled on a round trip, so velocity must be halved.

$$v = \Delta f\, c \,/\, (2 f_t)$$

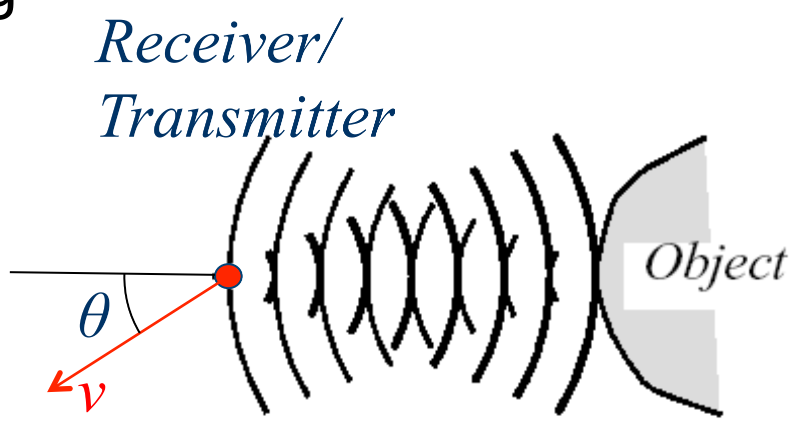


Doppler Effect Sensing

- Consider a reflected wave

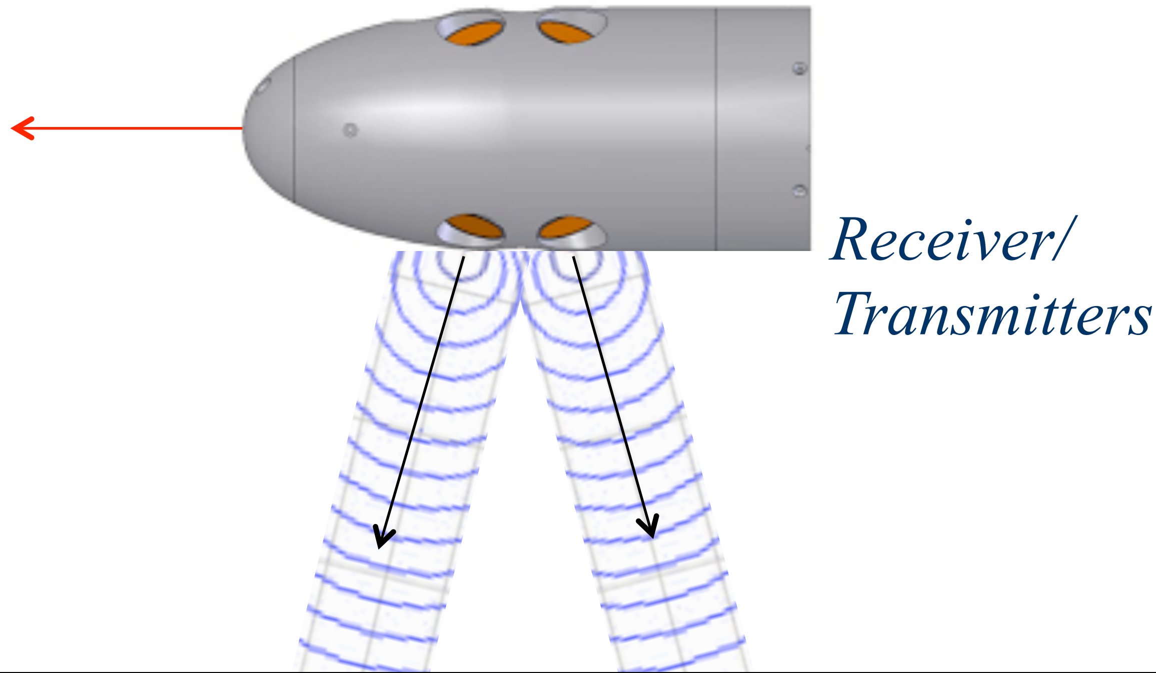
  … and if the R/T is moving away at relative angle θ

$$v = \Delta f\, c \,/\, (2\, f_t \cos\theta)$$



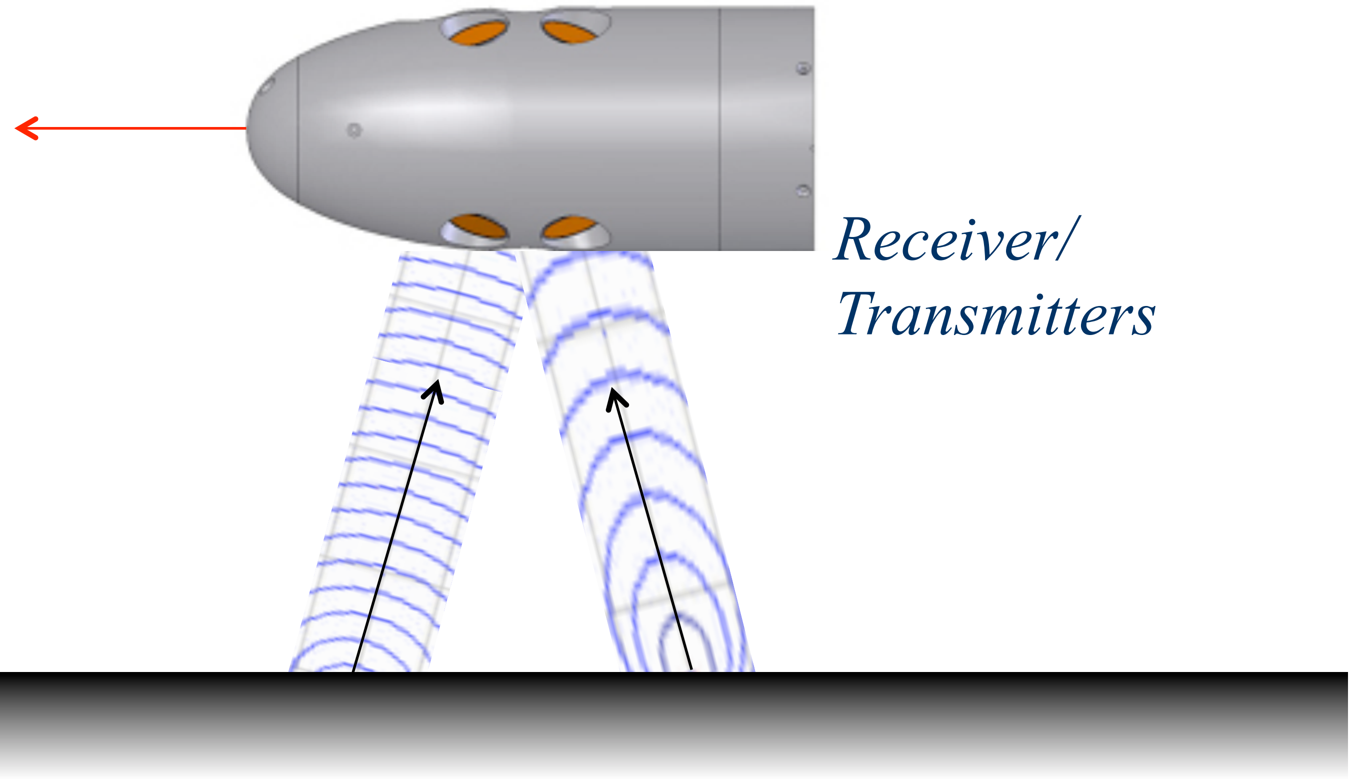
Doppler Effect Sensing

- Consider a DVL – Doppler Velocity Logger



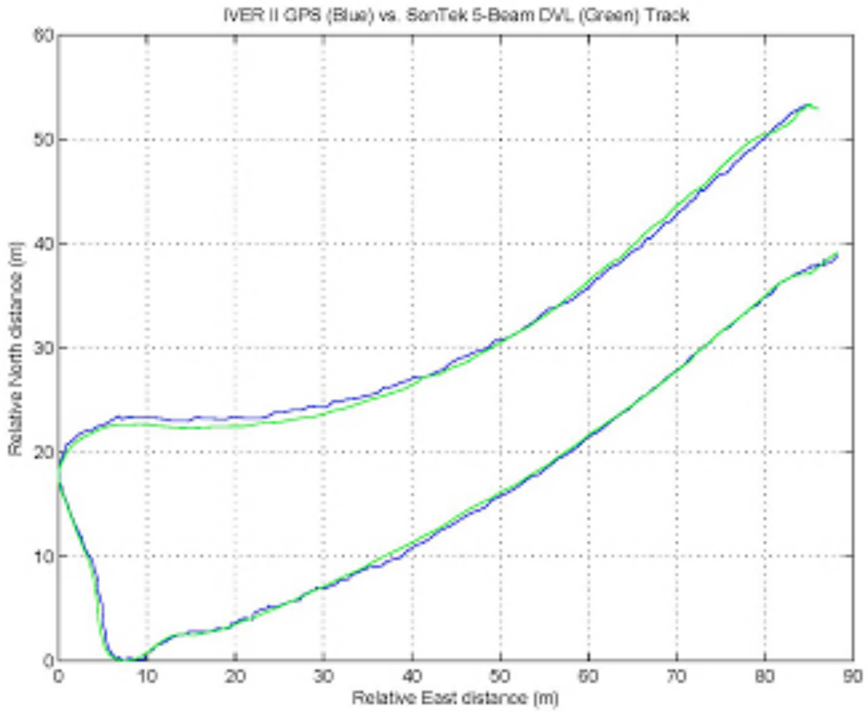
Doppler Effect Sensing

- Consider a DVL – Doppler Velocity Logger



Doppler Effect Sensing

- Iver2 DVL

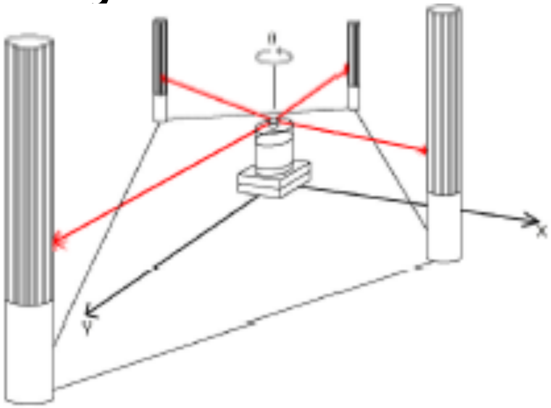


Outline – Sensors II

1. Doppler Effect Sensing
2. Beacon Positioning Systems
3. GPS
4. Compass
5. IMU

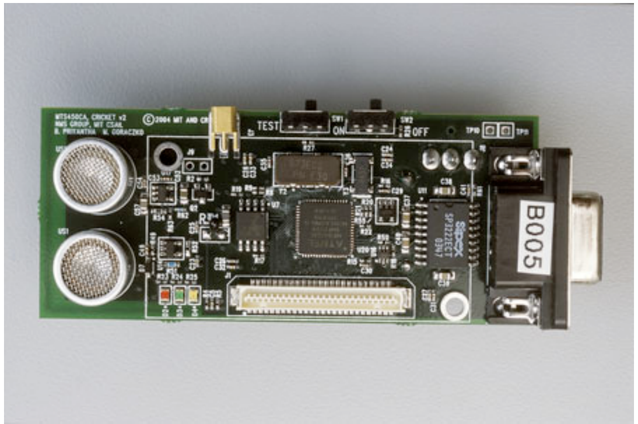
Ground-Based Beacon Systems

- Used for localization
- Used by humans (e.g. stars, lighthouses)
- Beacons can be active or passive
- Known location of beacons allows localization
- Problem is that they aren't flexible



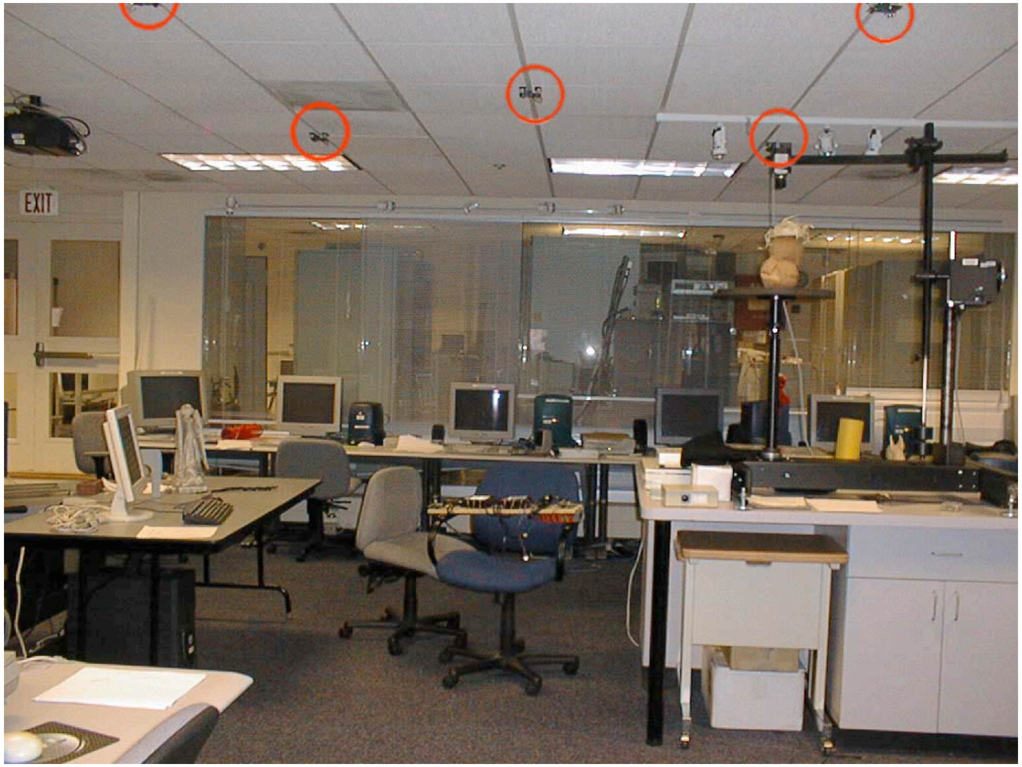
Ground-Based Beacon Systems

- MIT “Crickets” for Localization
  - Use acoustic beacons that allow for time-of-flight (then distance) measurements to a mobile transceiver.



Ground-Based Beacon Systems

- MIT Crickets (cont’)



Ground-Based Beacon Systems

- MIT Crickets (cont')

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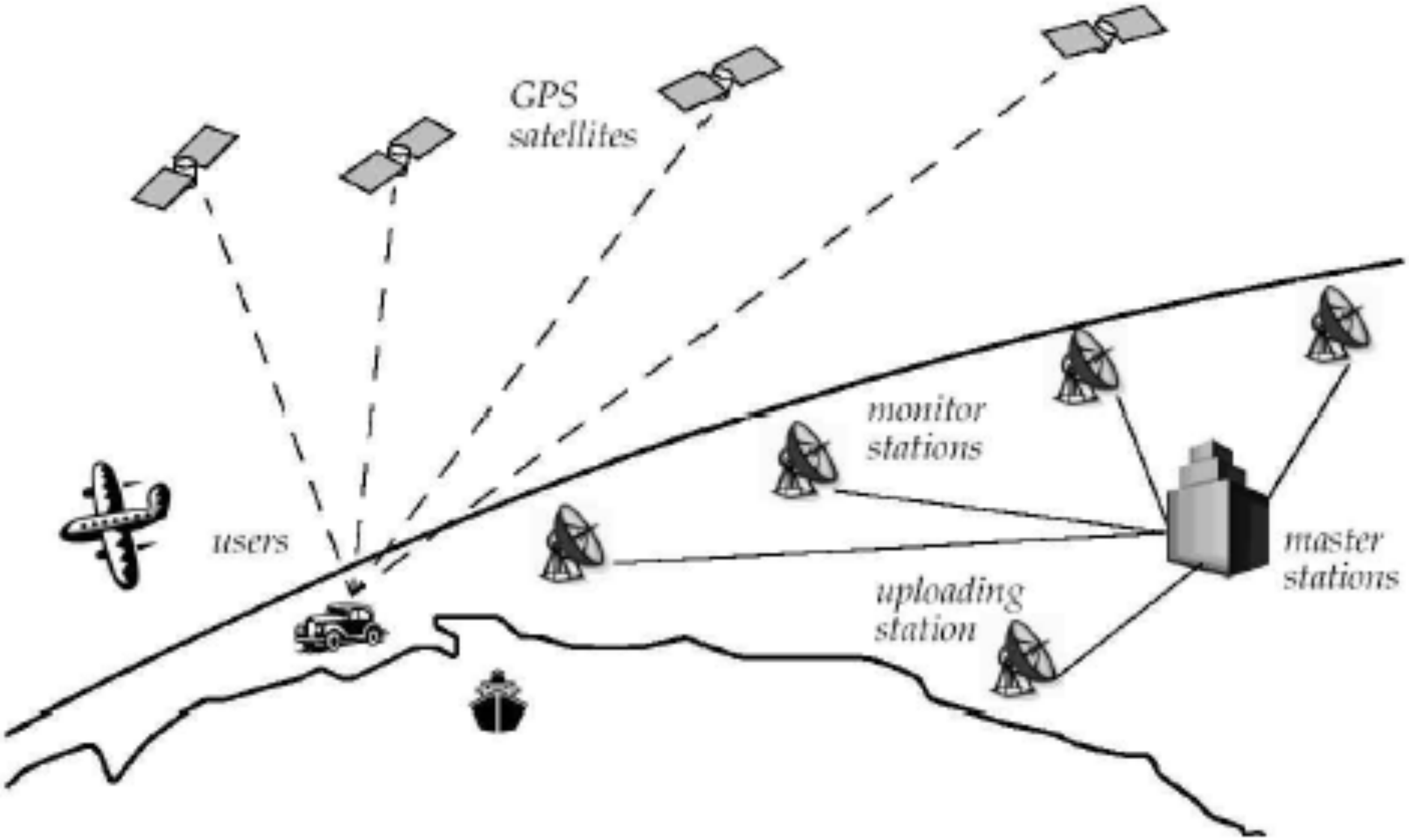
Global Positioning System (GPS)

- Developed for military use
- Now accessible for commercial use (e.g. hiking, flying, …)
- There are 24+ satellites orbiting the earth every 12 hours at height of 20+ km.
- There are 4 satellites located in each of 6 planes inclined at 55 degrees to the equator.

Garmin Image

Global Positioning System (GPS)



Global Positioning System (GPS)

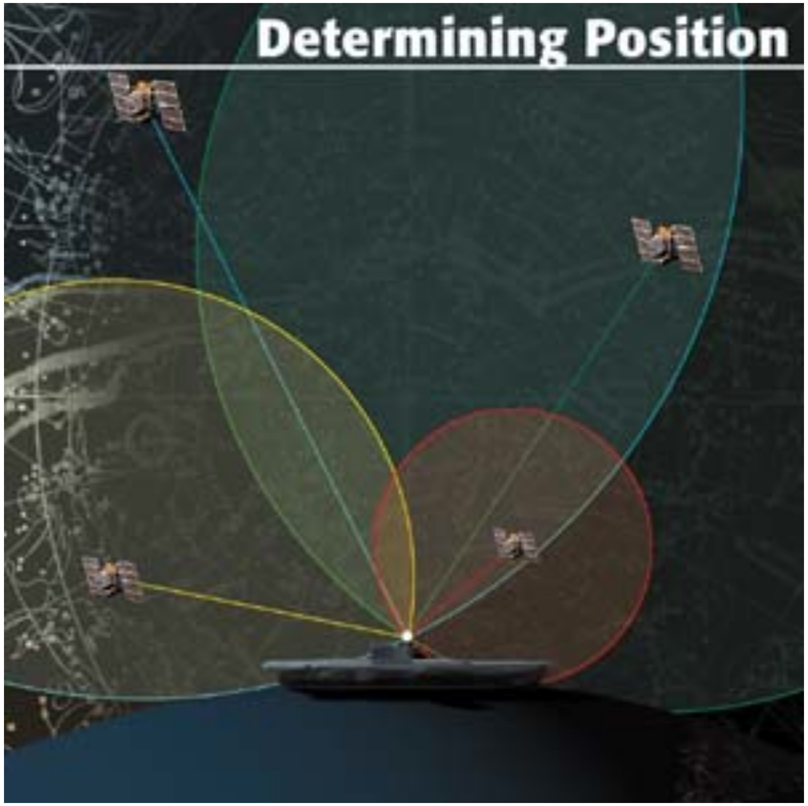
- Use a GPS receiver to measure time of flight from several satellites to receiver.
- The system requires:
  - Time synchronization between satellites and receiver
  - Known position of satellites
  - Precise measurement of time of flight
  - Overcoming interference with other signals

Global Positioning System (GPS)

- Time Synchronization:
  - Atomic clocks on each satellite are monitored from ground stations
- Known location of satellites
  - A number of widely distributed ground stations monitor the satellites
  - A master station analyses measurements and transmits position to each satellite

Global Positioning System (GPS)

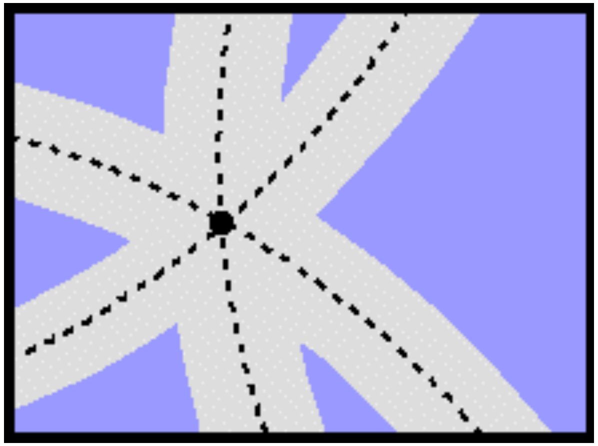
- Precise Measurement:
  - Satellites transmit (at the same time) their current time and location.
  - Arrival time differences inform the receiver of relative distance to each satellite.



http://airandspace.si.edu/gps/work.html

Global Positioning System (GPS)

- Precise Measurement:
  - Use four satellites to solve for *(x,y,z)*
  - But there are errors…



Global Positioning System (GPS)

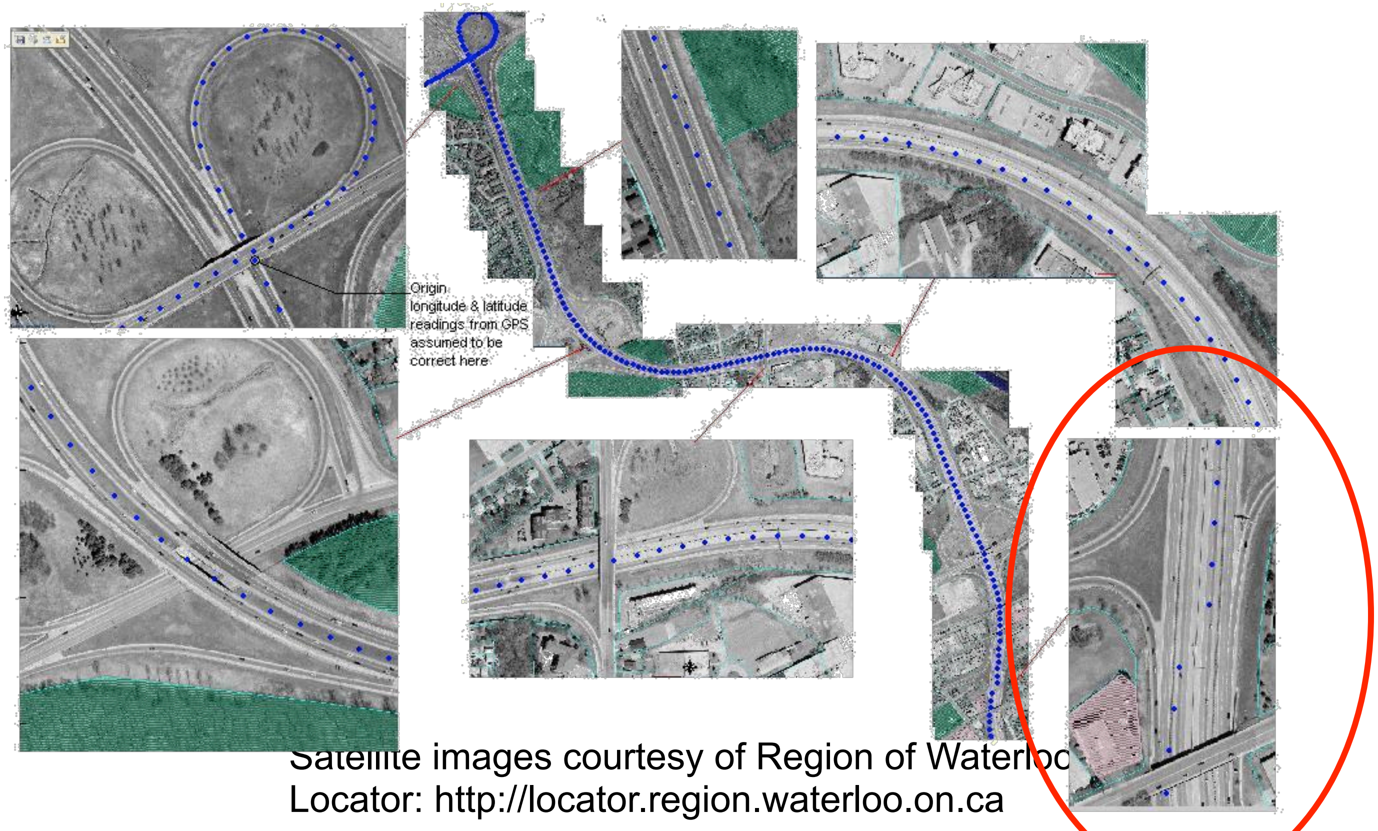
- Error Sources
  - Atmospheric conditions vary
  - Number of satellites with line of sight
  - Ephemeris Errors (position of satellite)
  - Satellite Geometry
  - Signal Multi-Path
  - Receiver Clock Errors

Global Positioning System (GPS)

- Regular GPS, can get accuracy 10-15 m.
- With a second receiver of known location, differential GPS (i.e. DGPS) can resolve down to 1 m.
- Carrier-phase can get resolution down to 1cm.

Global Positioning System (GPS)

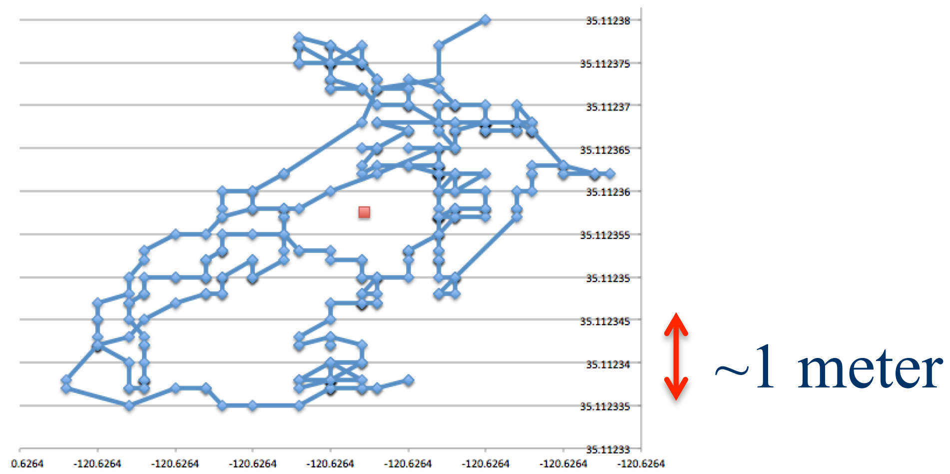
- Example:

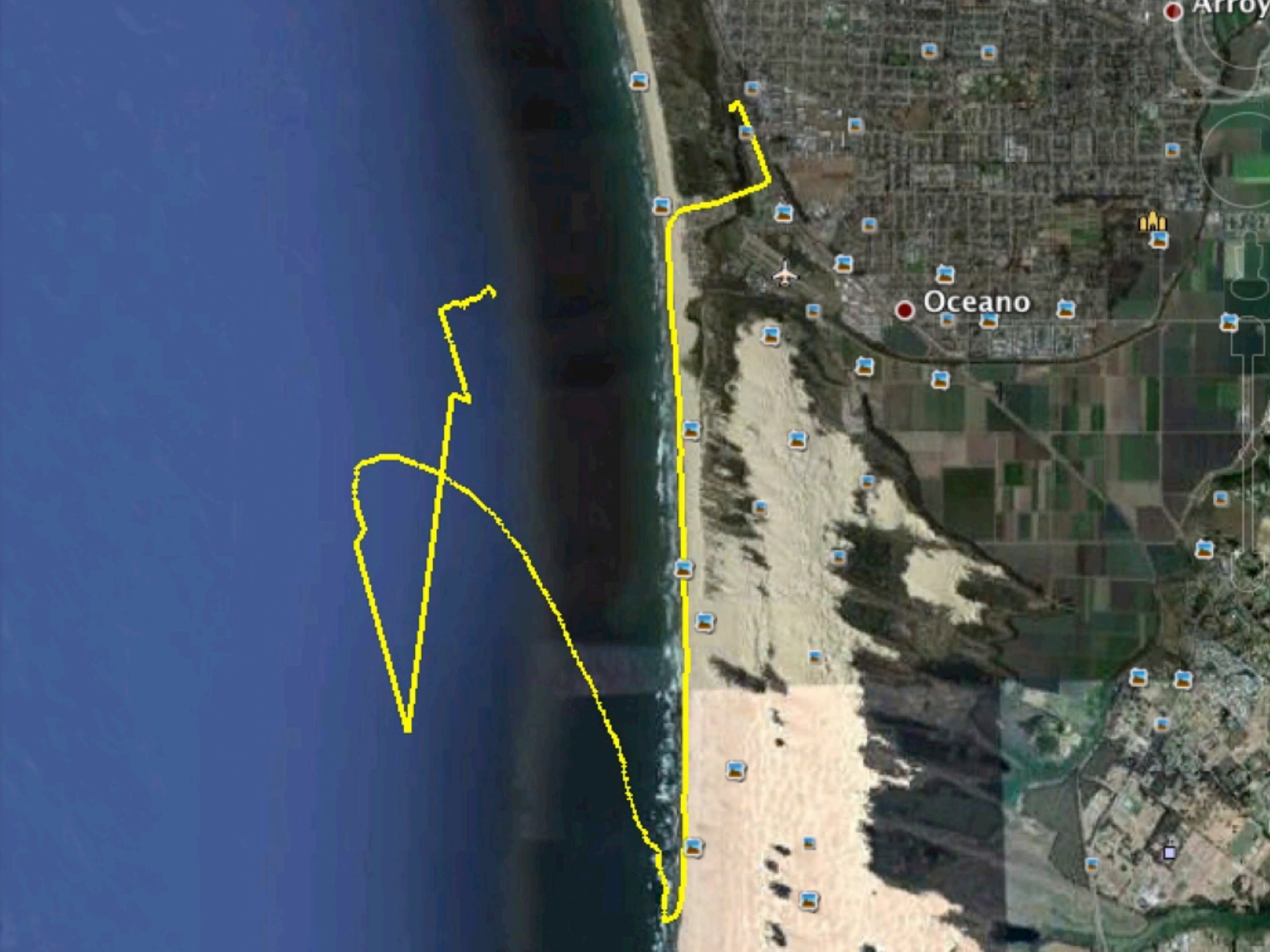


Satellite images courtesy of Region of Waterloo
Locator: http://locator.region.waterloo.on.ca

Global Positioning System (GPS)

- Example:




Oceano

Self-Calibrating PseudoLites

K9-SCPA field trial at the Marscape 02/11/04

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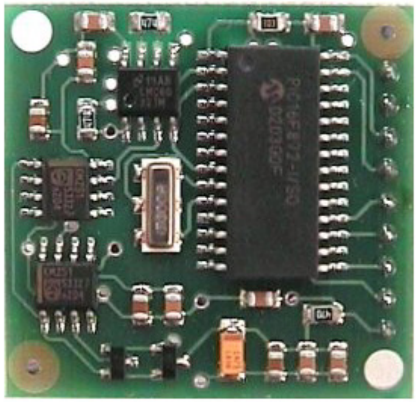
Compass

- Compass
  - Over 4000 years old
  - Uses earth's magnetic field to provide absolute measure for orientation
  - Disadvantages:
    - Earth's magnetic field is weak
    - Field is easily disturbed by other magnetic objects
    - Not dependable for indoor environments

Compass

- Example: Deventech Compass
  - good precision (0.1 degrees).
  - poor accuracy (within 3-4 degrees)



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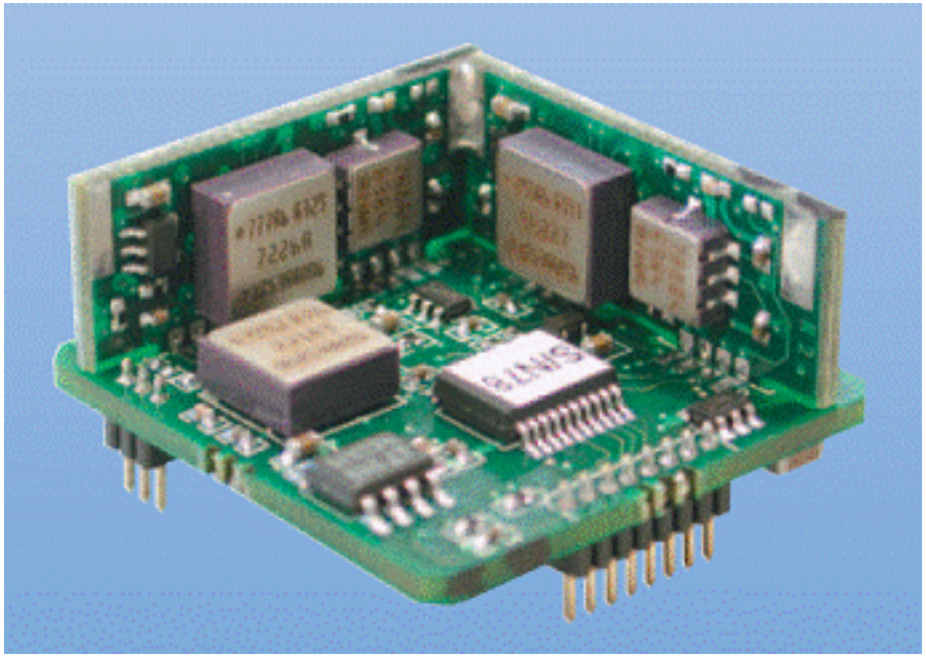
IMU

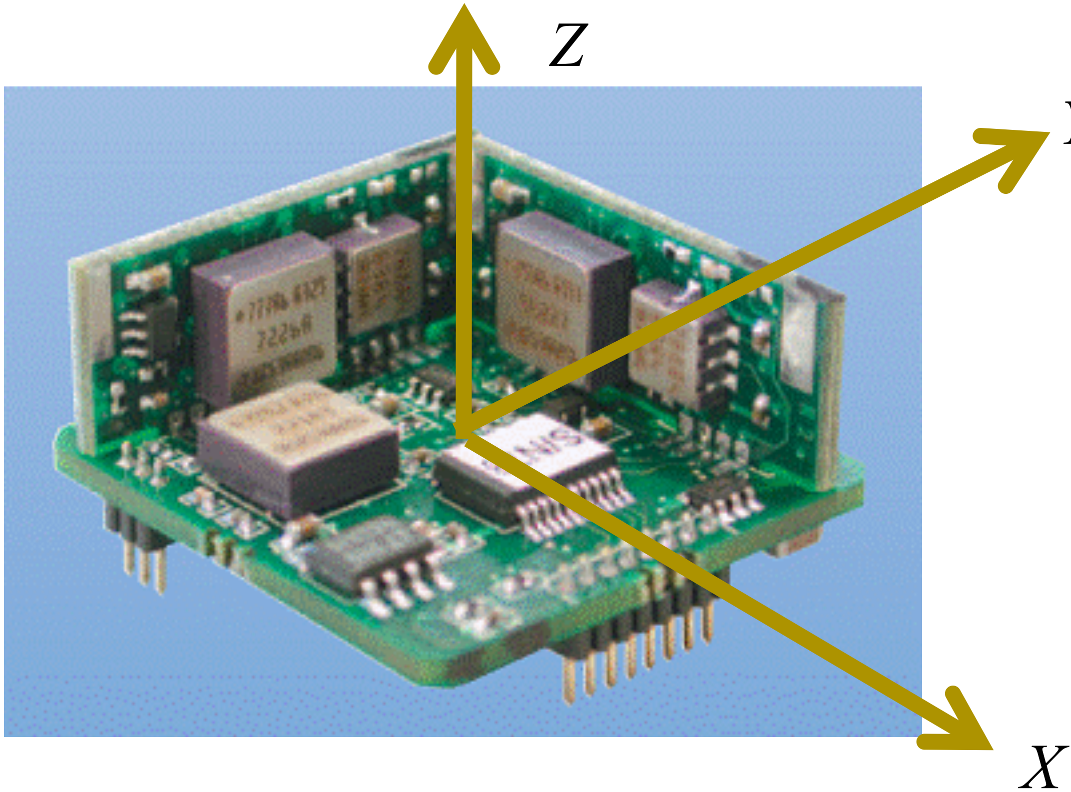
- Inertial Measurement Units
  - 3 Accelerometers
  - 3 Gyroscopes
  - 3 Magnetometers(?)



www.barnardmicrosystems.com

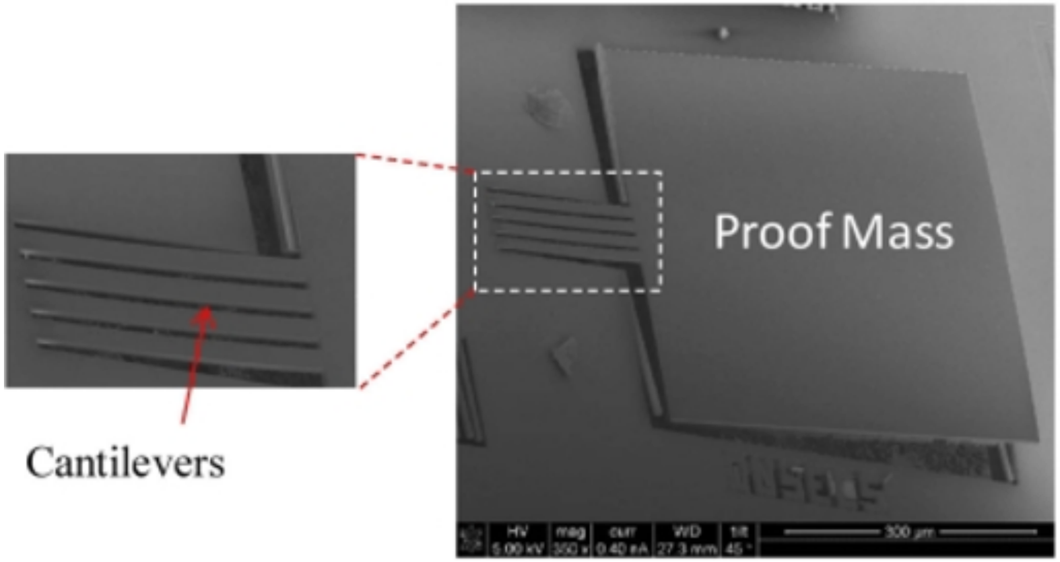
IMU

- Inertial Measurement Units



IMU

- Accelerometers
  - The accelerometers are typically MEMS based
  - They are small cantilever beams



Khir MH, Qu P, Qu H - Sensors (Basel) (2011)

IMU

- Accelerometers
  - Their deflection x is measured, to establish a force

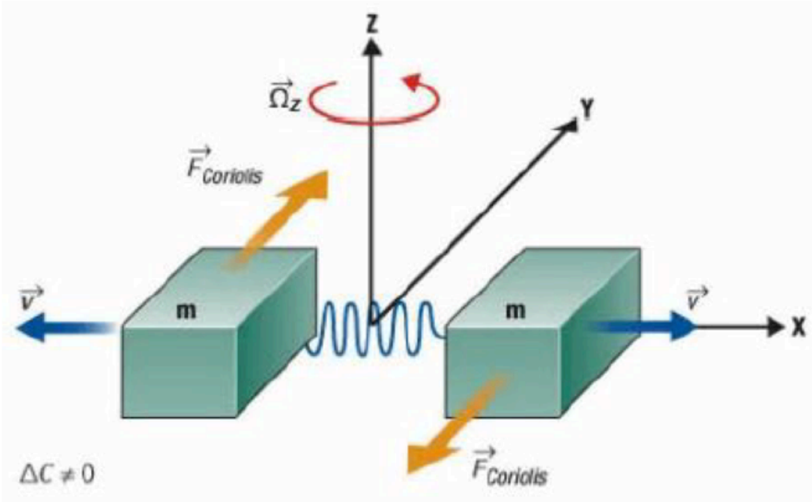
$$F = kx$$

  - The acceleration is obtained since the mass is known

$$a = F/m$$

IMU

- (MEMS) Gyroscopes
  - Two masses oscillate back and forth from the center of rotation with velocity v.
  - A rotation will cause a Coriolis force in this coordinate frame.



IMU

- Gyroscopes
  - Their deflection y is measured, to establish a force

$$F_{Coriolis} = ky$$

  - The acceleration is obtained since the mass is known

$$-2m\,|\boldsymbol{\Omega} \times \boldsymbol{v}| = F_{Coriolis}$$

IMU

- Gyroscopes
  - Their deflection y is measured, to establish a force

$$F_{Coriolis} = ky$$

  - The acceleration is obtained since the mass is known

$$-2m\,|\boldsymbol{\Omega} \times \boldsymbol{v}| = F_{Coriolis}$$

IMU

- Integration
  - The position of an IMU can be predicted through double integration

$$v(\tau + \delta t) = v(\tau) + \int_{\tau}^{\tau+\delta t} [a(t) - \mathbf{g}]\,dt$$

$$x(\tau + \delta t) = x(\tau) + \int_{\tau}^{\tau+\delta t} v(t)\,dt$$

IMU

- Integration
  - Integration is often accomplished using the trapezoidal rule
  - *ERRORS ACCUMULATE! = DRIFT*