The Global Positioning System and its use for Control of Ground Vehicles

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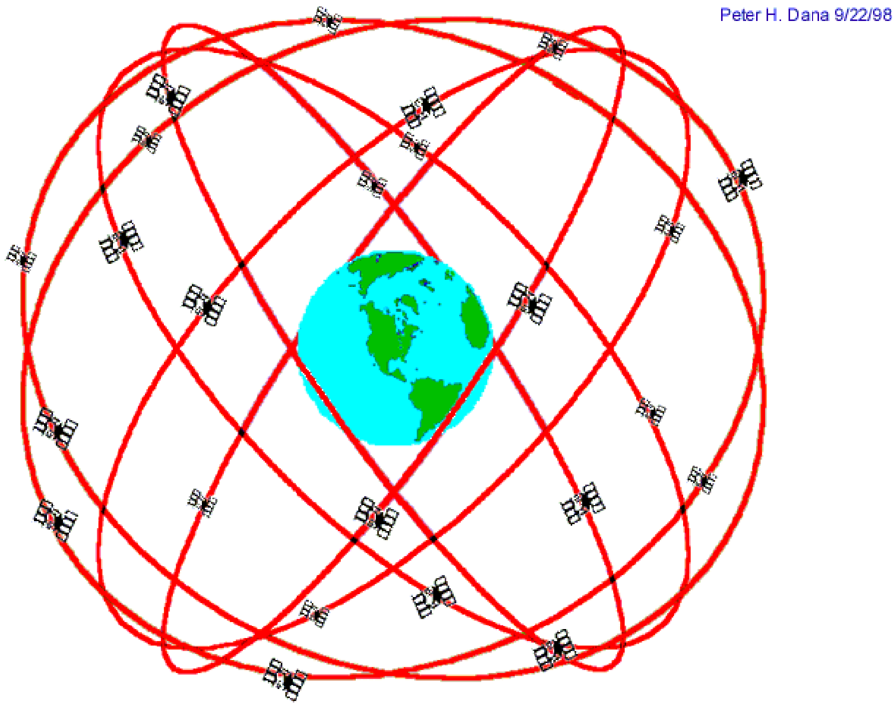
Control of Vehicles

- need to know vehicle:
  - position
  - velocity
  - direction of travel
  - orientation
- above measurements can be made using GPS
- can use the measurements (for example) to:
  - control farm vehicles
  - improve safety systems in passenger cars

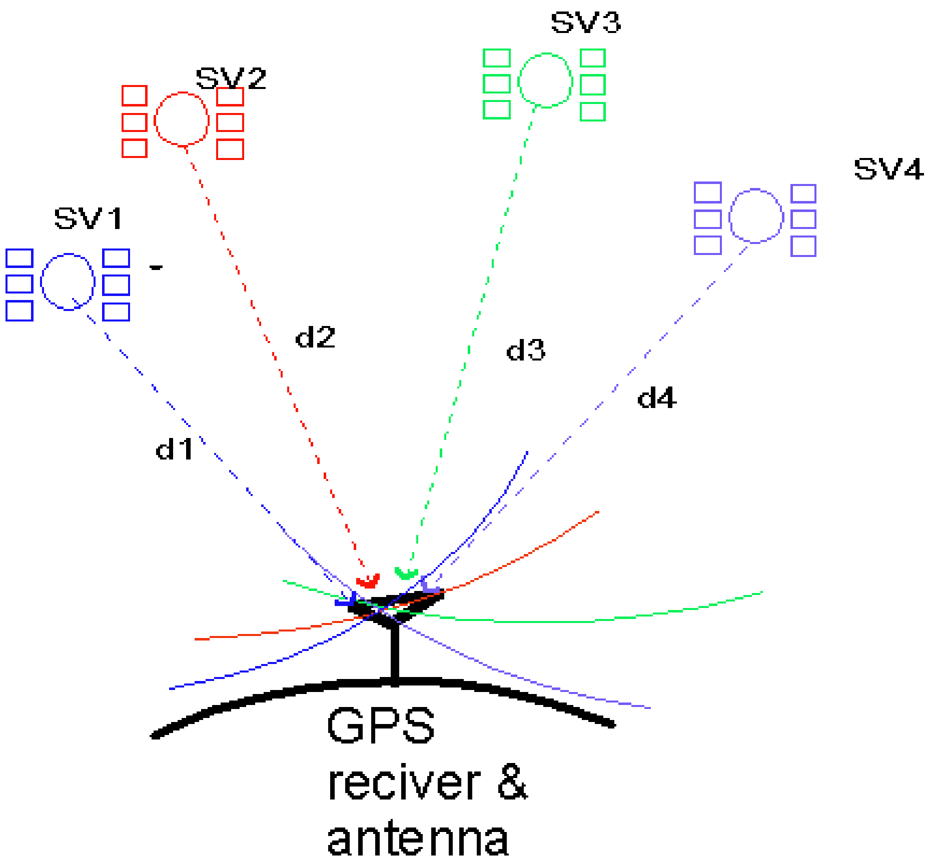
Global Positioning System (GPS)



GPS Nominal Constellation
24 Satellites in 6 Orbital Planes
4 Satellites in each Plane
20,200 km Altitudes, 55 Degree Inclination

- 24+ satellites in well known orbits providing precise ranging source
- 6 orbital planes
- 55° inclinations
- 12 hour orbits
- 20,200 km orbits
- Ground track repeats every 23:56:04

How GPS Works



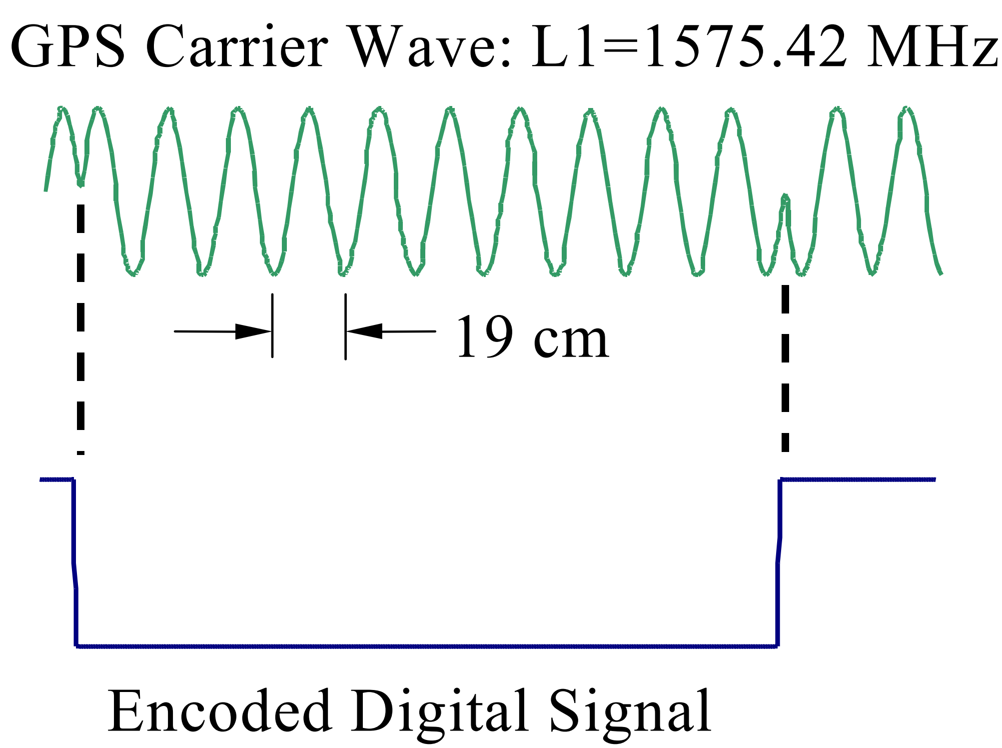
- measure the transit time for a signal from SV to user
  - multiply by *c* to get range
  - triangulate ranges to get position (and time)

GPS Facts

- There are more than 100 times as many civilian users than military users.
- 5 million recreational GPS devices were shipped in 2003, with a projected growth rate of 31% each year through 2009.
- Economics:
  - The cost of maintaining the GPS satellite system is $750 million each year, including replacing aging satellites.
  - The direct economic impact of GPS is projected to exceed $50 billion by 2010

http://gps.losangeles.af.mil/jpo/gpsoverview.htm

GPS Signal (-160 dBw ~ 10^{-16} watts)



digital code:
(satellite info)

- satellite #
- time
- location
- velocity

Roughly equivalent to viewing a 25-watt light bulb from a distance of 10,000 miles.

GPS Broadcast Signal Structure

- Each satellite transmits the precise time (UTC-USNO), the complete parameters of its orbit, and the major parameters of all other satellite's orbits
  - These parameters are collectively known as *ephemeris data.*
- The Navigation message which includes the ephemeris data from the satellite is 30 secs. in duration and is transmitted in digital form at a rate of 50 bps.
- This data transmission modulates the GPS carrier wave using *binary phase-shift keying* (BPSK)

Gold Codes and Spread-Spectrum Transmission

- Gold Codes are a family of unique binary sequences which have very low cross-correlation with other sequences in the family and low auto-correlation as well.
- Modulating each GPS satellite's signal by a unique Gold Code, known as the PRN number, spreads the signal over a wider bandwidth, which provides noise rejection and enables multiple access (CDMA).
  - Allows satellites transmit on the same frequency at the same time without interfering with each other

Carrier Wave

- L1 at 1575.42 MHz (154 x 10.23 MHz)
- L2 at 1227.60 MHz (120 x 10.23 MHz)
- Modulated with Code and Navigation Data using Binary Phase-Shift Keying (BPSK)
- C/A and P(Y) are transmitted orthogonally on L1

Code Signal

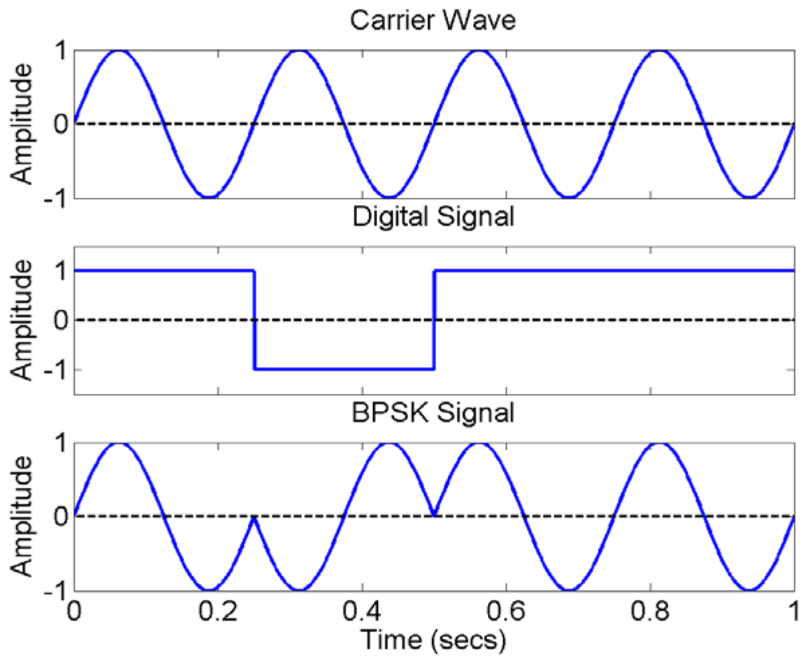
- Code Division Multiple Access (CDMA)
- Course Acquisition - C/A
  - Gold Codes
  - Code Period of 1 ms
- Precision Code - P(Y)
  - Anti-Spoofing Mode
  - Code reset each week

GPS Signal Structure

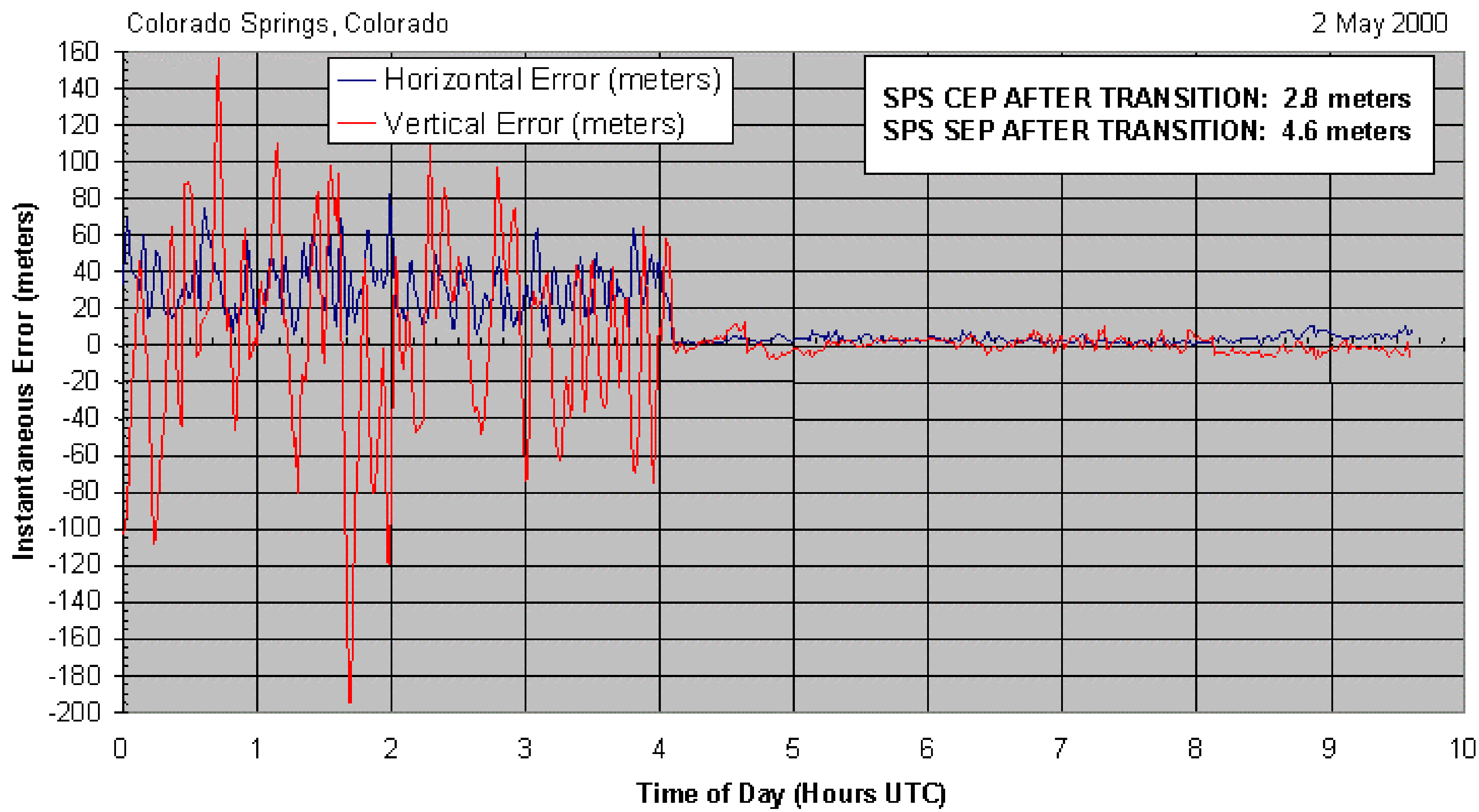
$$S_{L_{li}}(t) = \sqrt{2P_c}\, XG_i(t) D_i(t) \cos(\omega_1 t + \phi) + \sqrt{2P_p}\, XP_i(t) D_i(t) \sin(\omega_1 t + \phi)$$

$$S_{L_{li}}(t) = \sqrt{2P_c}\, XG_i(t) D_i(t) \cos(\omega_1 t + \phi)$$

Signal = C/A x Data x Carrier



SA Transition -- 2 May 2000



Differential GPS (DGPS)

Error Source	GPS (m)	DGPS (m)
Ionosphere	5	~0
Troposphere	0.5	~0
SV Clock	1	~0
SV Ephemeris	1	~0
Receiver Noise	0.5	0.5
Multi-path	0.5	0.5
SA	30	~0
Total	~5-40	~1.0

Use a Base Station (at known location) to correct common GPS errors

GPS Position Accuracy (1σ)

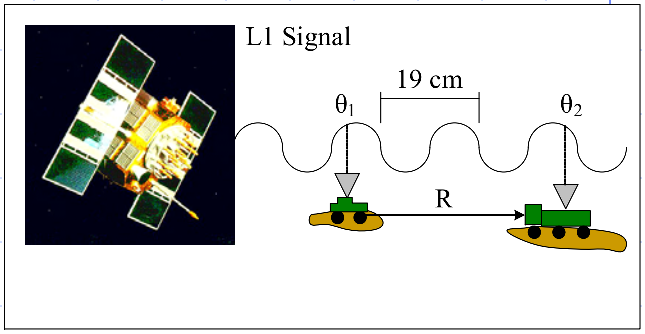
- Military Stand Alone (No SA) ~3m, global coverage
- Civil Stand Alone (w/ SA) ~30m, global coverage
- Code Phase Differential (DGPS) ~0.1m-1m not all are global, but almost full US coverage
  - local reference station (~0.3m)
  - Coast Guard differential corrections ~ 0.5m
  - WAAS ~1-3m
  - OmniStar VBS (~1m) & Omnistar HP (~10cm)
  - JohnDeere Starfire (~10cm)
- Carrier Phase Differential ~2cm, local (~10km) coverage

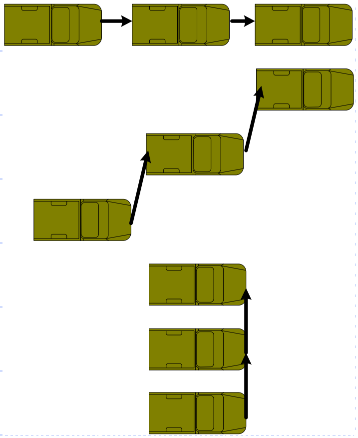
USDOT NDGPS & HA-NDGPS

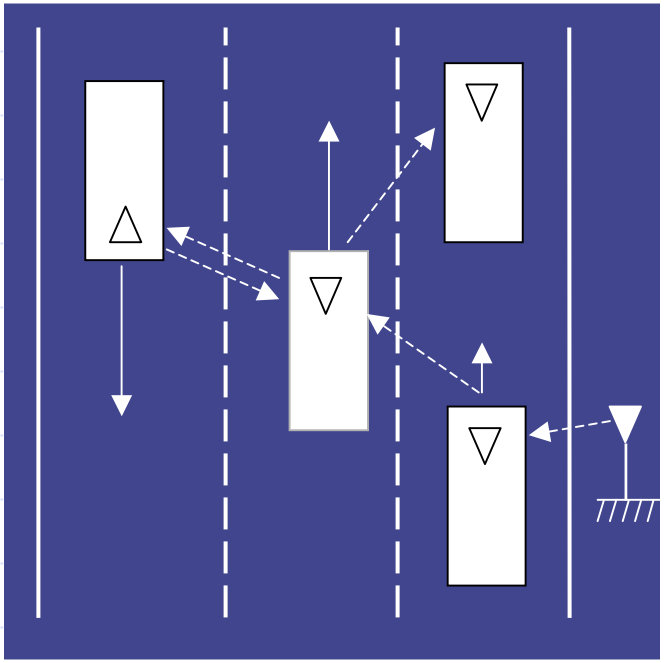
- Nationwide Differential GPS
  - FHWA as Part of USDOT ITS
  - 1-3 m accuracy
  - Enable improved collision notification systems, cooperative vehicle-highway collision avoidance systems, and more accurate in-vehicle route guidance systems
- High-Accuracy NDGPS
  - Goal of 10cm horizontal accuracy
  - monitored to ensure it is providing the accuracy needed to meet safety-of-life applications.
  - service uses quad-frequency receivers to enable interpolation between broadcast sites
  - employs a low radio frequency broadcast technique

Relative GPS Positioning Using Dedicated Short Range Communication

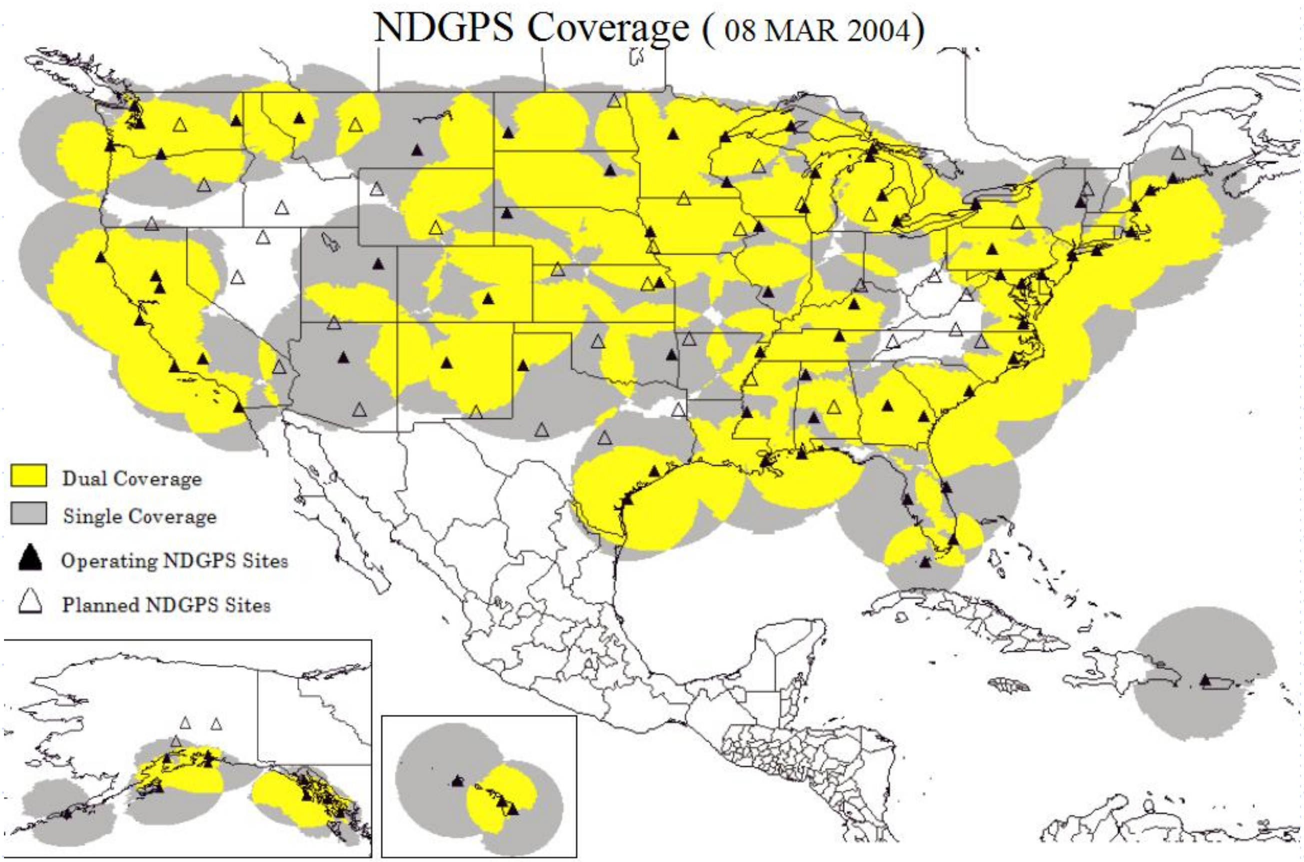
- Utilize DSRC (5.85-5.925 GHz) to pass information between vehicles and roadside stations
- Some information may be position and direction pertinent
- Determine relative position of vehicles (relative DGPS) on highways or automated convoys



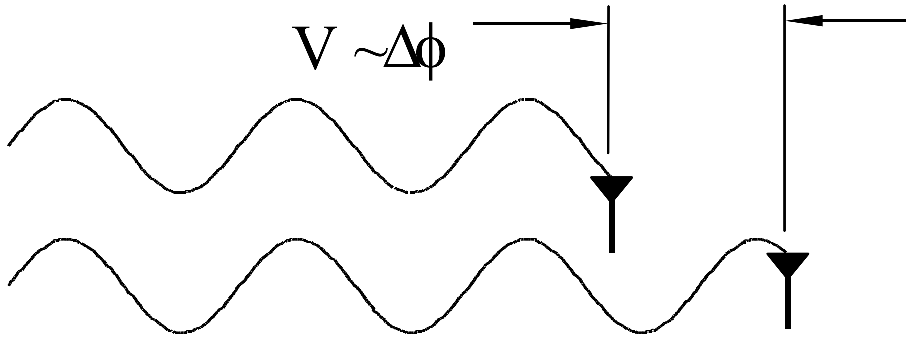


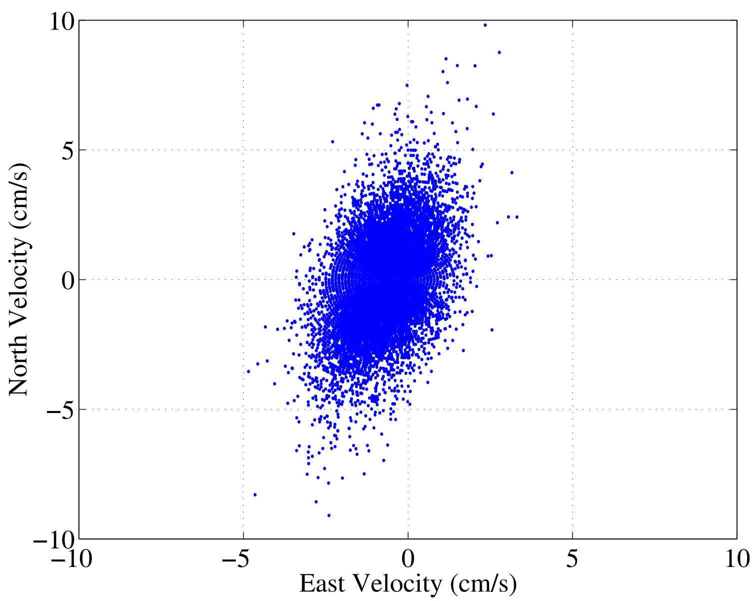


NDGPS Coverage



GPS Velocity





No Reference Station Required

Accuracy
- ≈ 0.2-0.5 m/s with SA
- ≈ 3-5 cm/s without SA

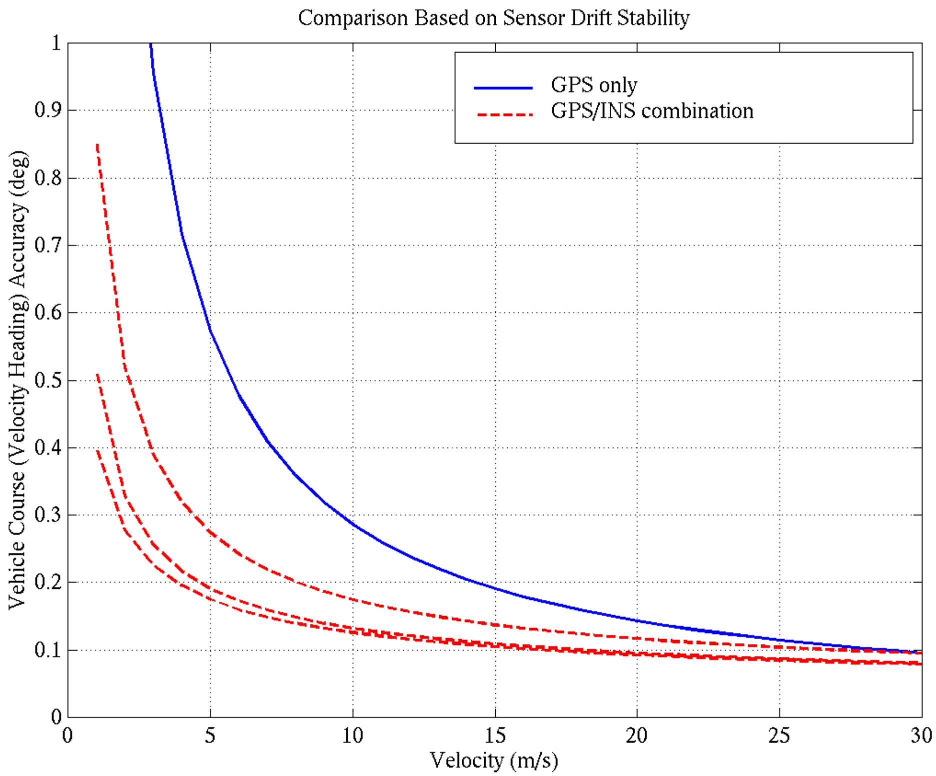
Provides accurate measurements to correct IMU errors

GPS/INS: The Perfect Complement

GPS (Low Frequency Sensor)	INS (High Frequency Sensor)
▪ Limited to 1-20 Hz ▪ Stable over long periods of time ▪ Stochastic zero mean noise ▪ Unbiased ▪ Noisy	▪ Higher output rates available ▪ Drift over long periods ▪ Noise due to vehicle dynamics ▪ Biased

➢ **The combination provides a high update rate, low noise, unbiased measurement solution**

GPS Velocity Based Heading Accuracy



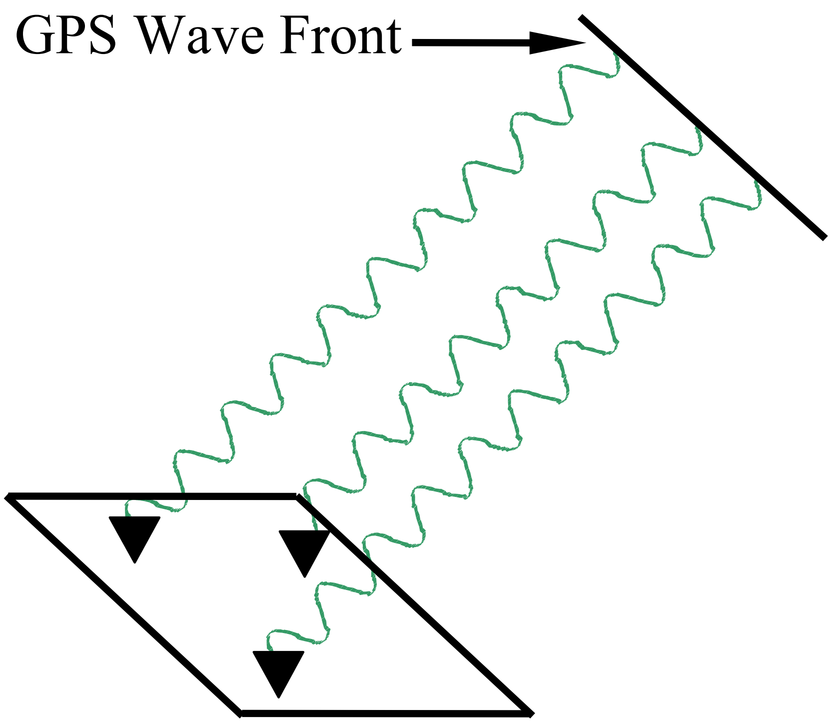
$$\sigma_{\psi} = \frac{\sigma_{vel}}{V} \approx \frac{0.05}{V} \text{(rad)}$$

Heading accuracy based on
E-N GPS velocity noises

GPS Attitude

No Reference Station Required

Accuracy Depends on Antenna Spacing (Not Velocity)

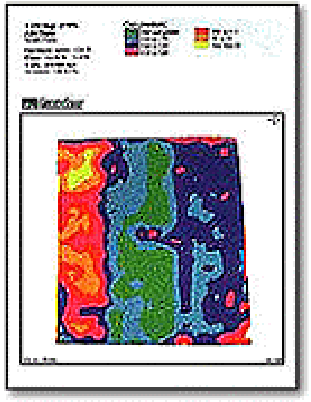


Compare the GPS measurements at 3 fixed antennas:

- Roll
- Pitch
- Yaw

accuracy = 0.1°
(w/ 2m baseline)

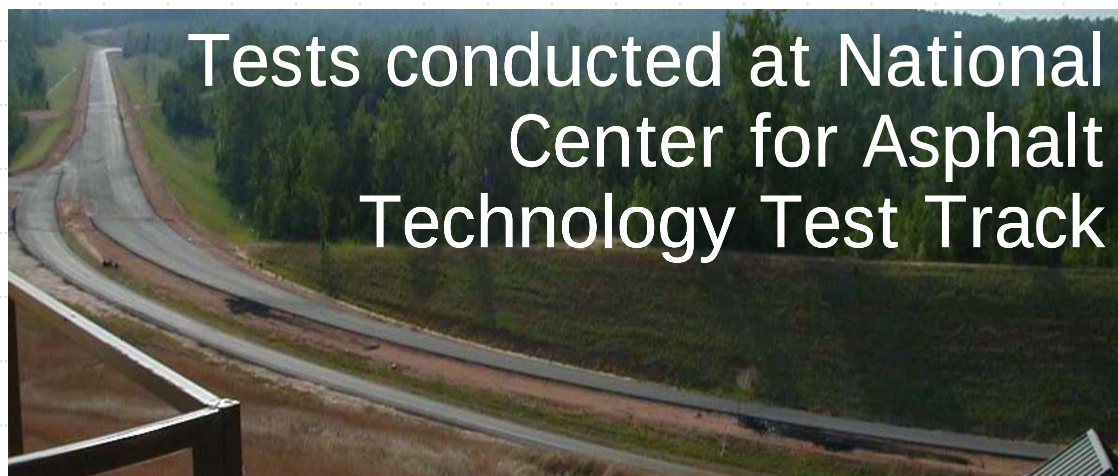
Uses of GPS



Vehicle Estimation

Infinity G35:

- GPS Velocity & Position
- 6 DOF IMU
- Steer angle
- Wheel Speed

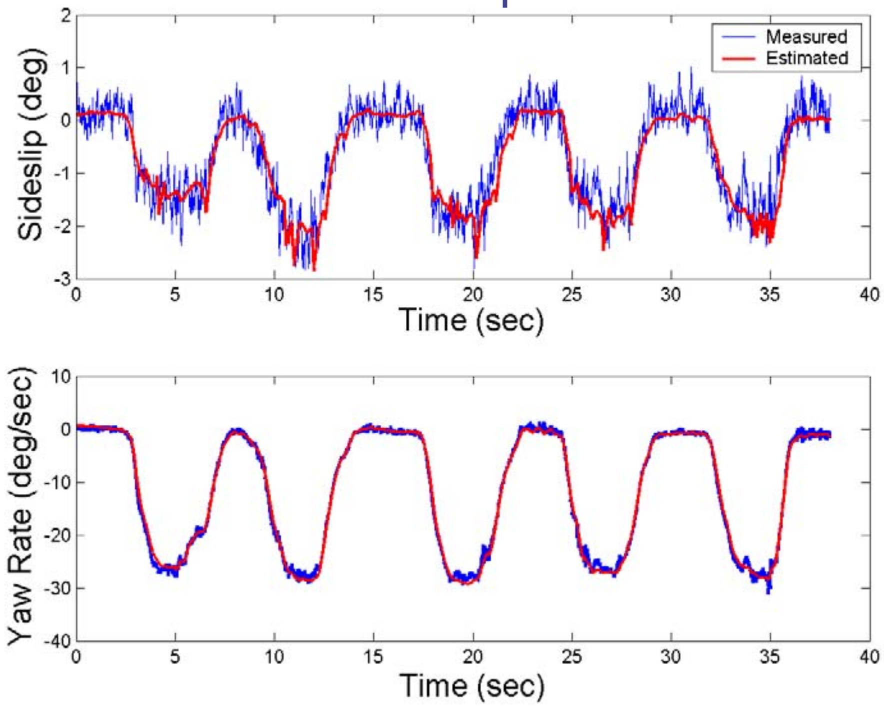


Tests conducted at National Center for Asphalt Technology Test Track

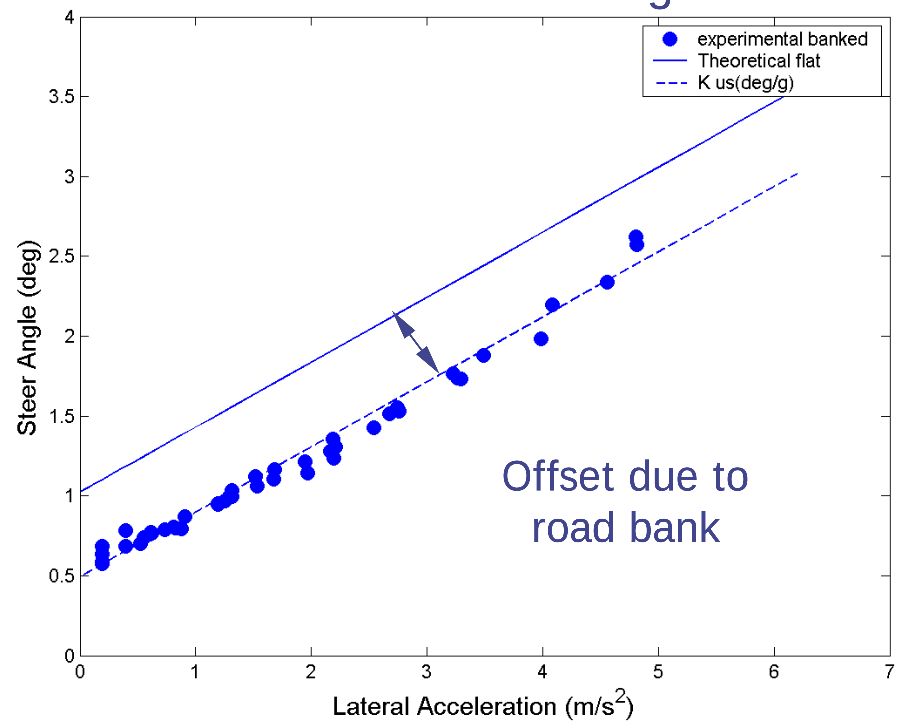
Vehicle State and Parameter Estimation

- Estimate vehicle parameters and states that may otherwise:
  - be difficult to measure
  - require expensive sensors
- Uses GPS and low cost inertial sensors with a vehicle test-bed

Estimation of Sideslip and Yaw Rate

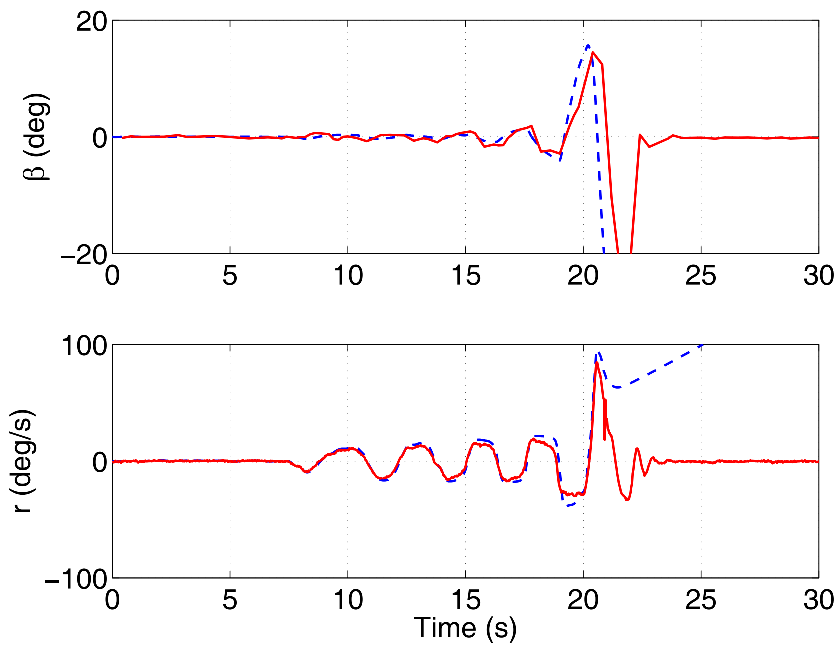


Estimation of Understeer gradient

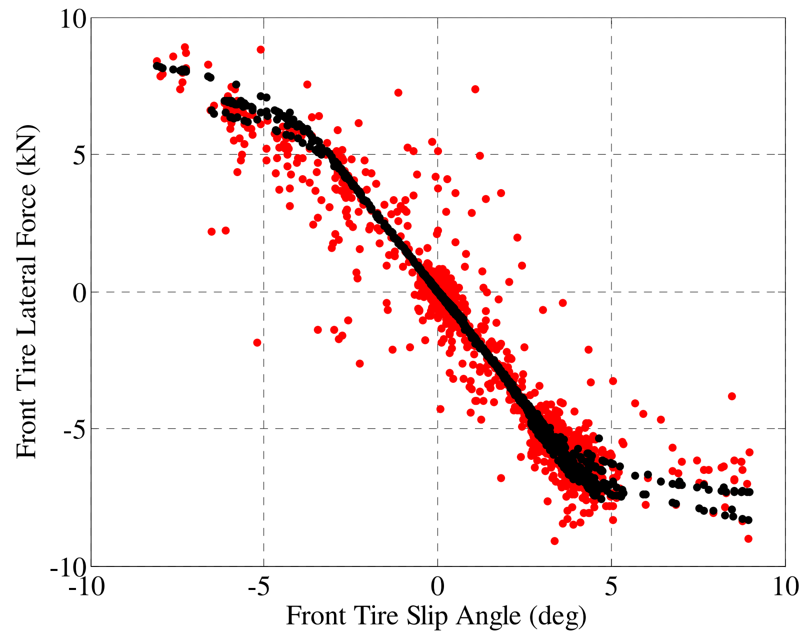


Tire Estimation

Simulated vs. Experimental Vehicle Data



Experimental Data vs. Estimated Tire Model



Motivation for GPS Guided Tractors

- 1999 tractor sales
  - North America - 108K
  - World - 590K

- good satellite visibility on farms
- relieve drivers from tedious & monotonous labor
- provide farm operation during poor visibility
- open doors for new agricultural techniques

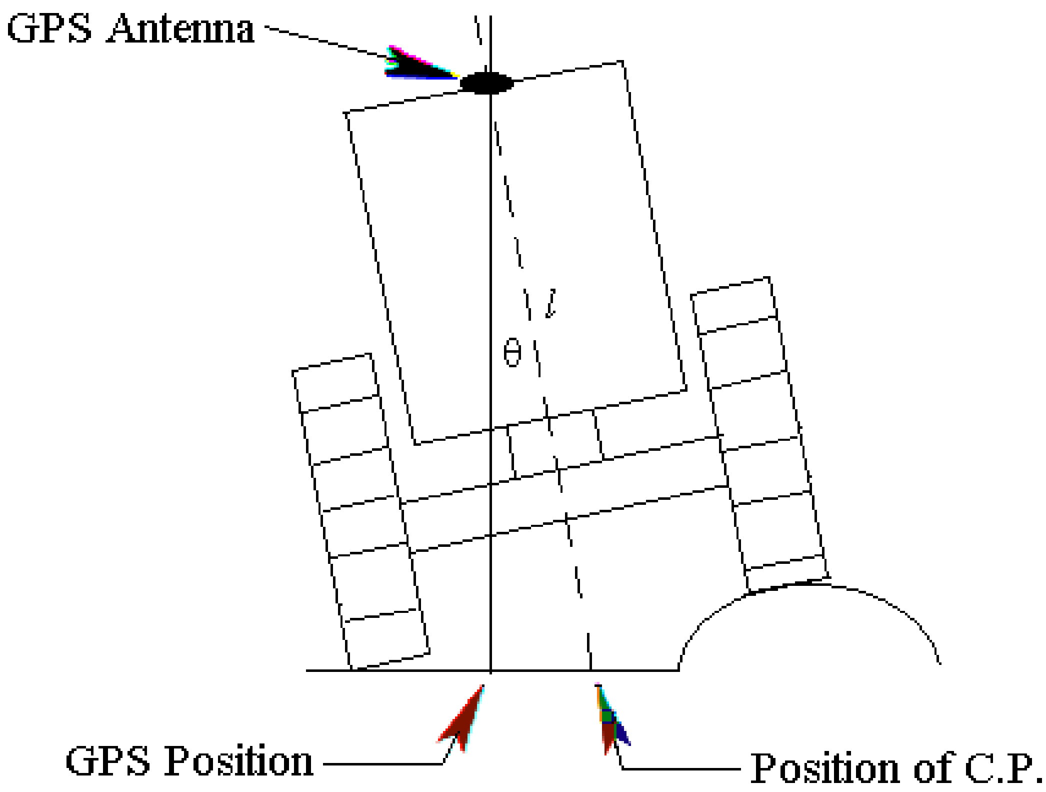
Automated Steering

- Cm-level control for row crops
- Reduced overlap for tillage
- Cooperating Vehicles

GPS Guided Farm Tractor

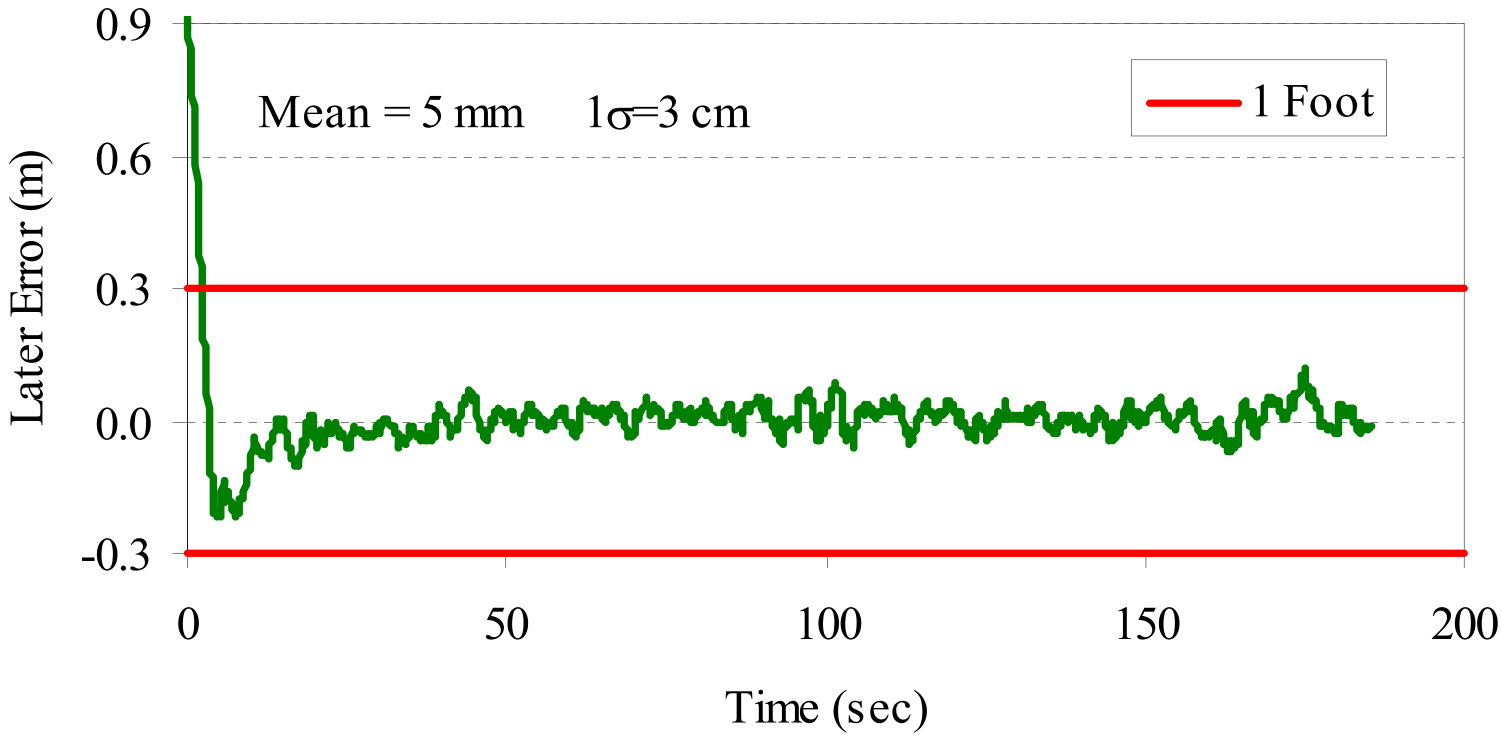
- 4 - antenna carrier phase DGPS
- 3-D position (1σ = 2 cm)
- 3 axis attitude (1σ = 0.1°)
- 5 Hz update rate
- steer angle potentiometer

Lever Arm Correction

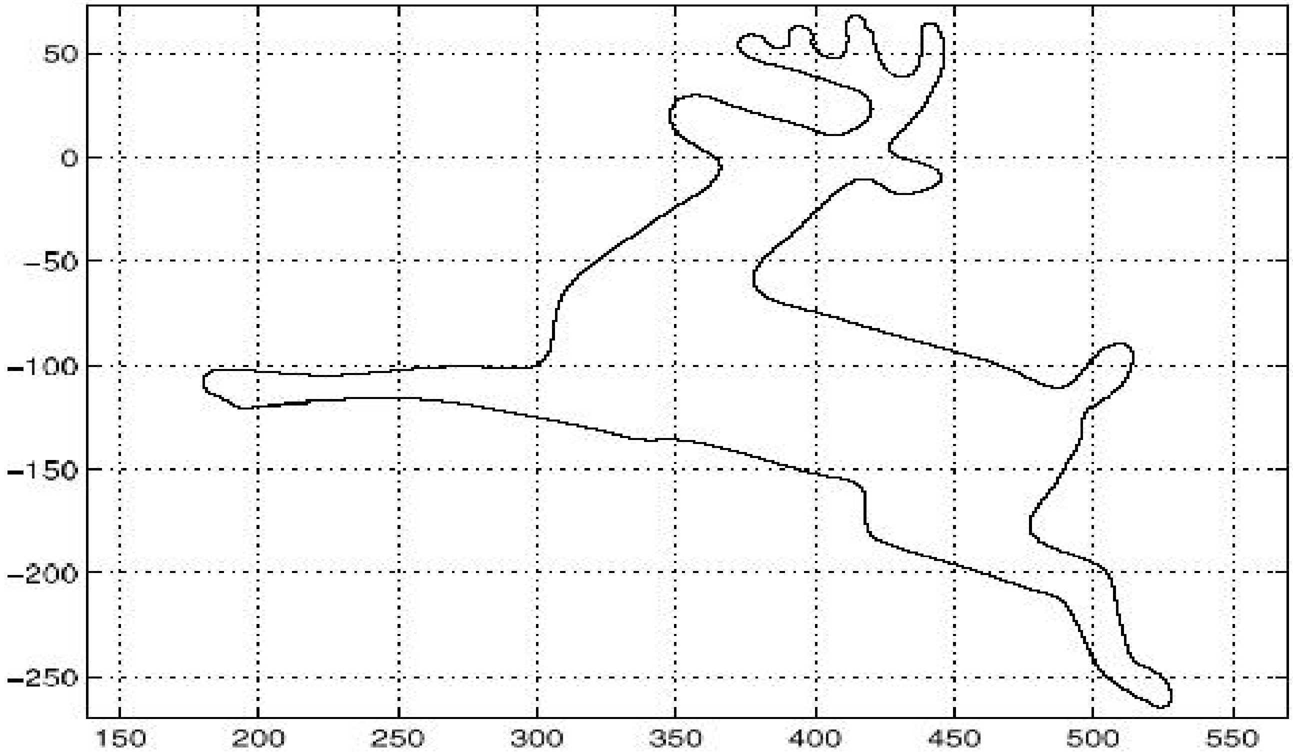


- ~ 3 meter lever arm
- 0.4° roll accuracy required to utilize 2 cm DGPS position accuracy

Line Tracking



Advanced Trajectories



DARPA Grand Challenge

Race from Los Angeles to Las Vegas

- No prior knowledge of route
- No drivers allowed

DARPA's Motivation

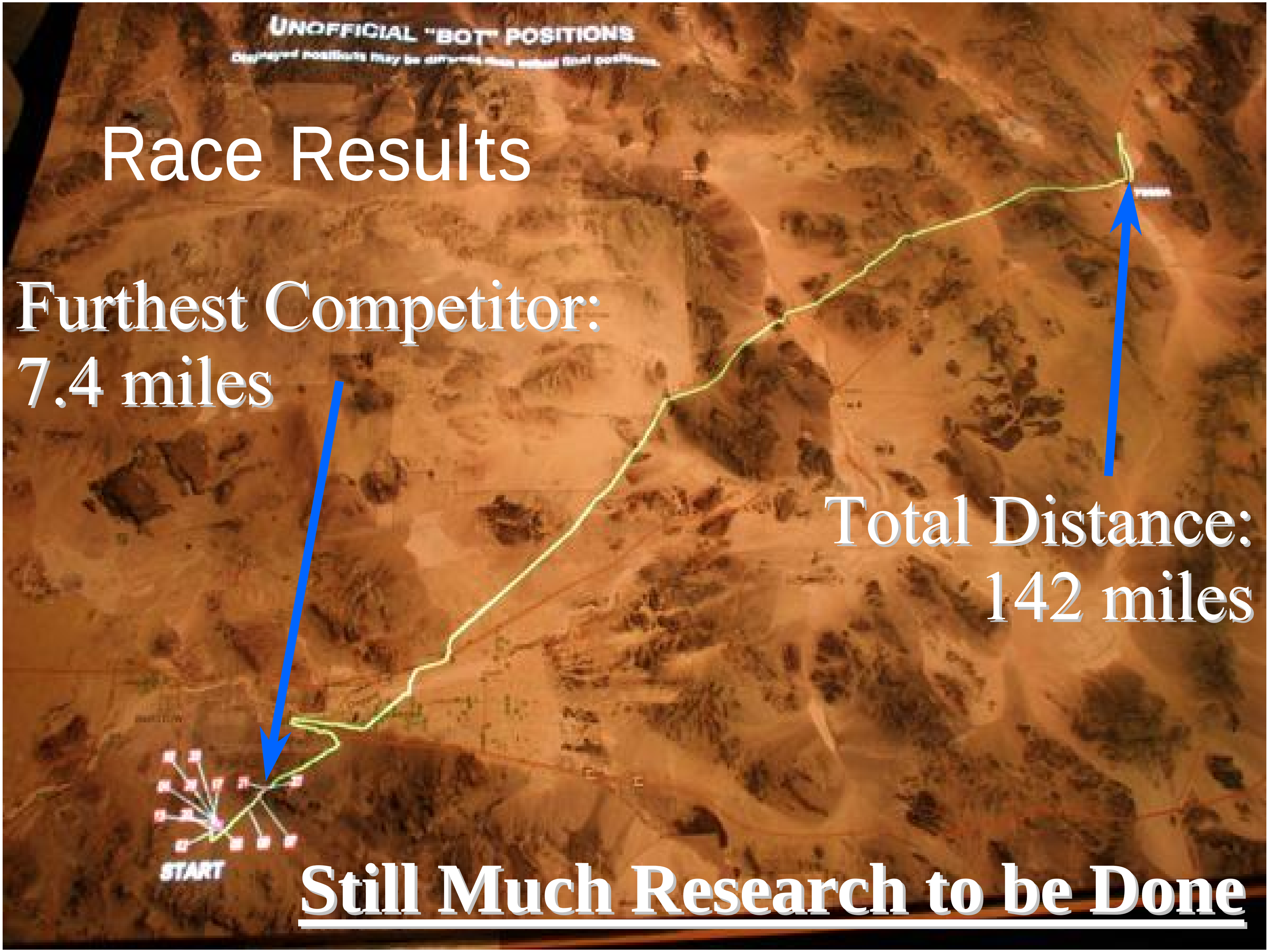
"This challenge is intended to spur the accelerated development of autonomous ground vehicle technology for military applications, and is the first in a series of Grand Challenges planned by DARPA."

-DARPA press release

April 24, 2003

Why Again?

Race Results



Furthest Competitor:
7.4 miles

Total Distance:
142 miles

Still Much Research to be Done

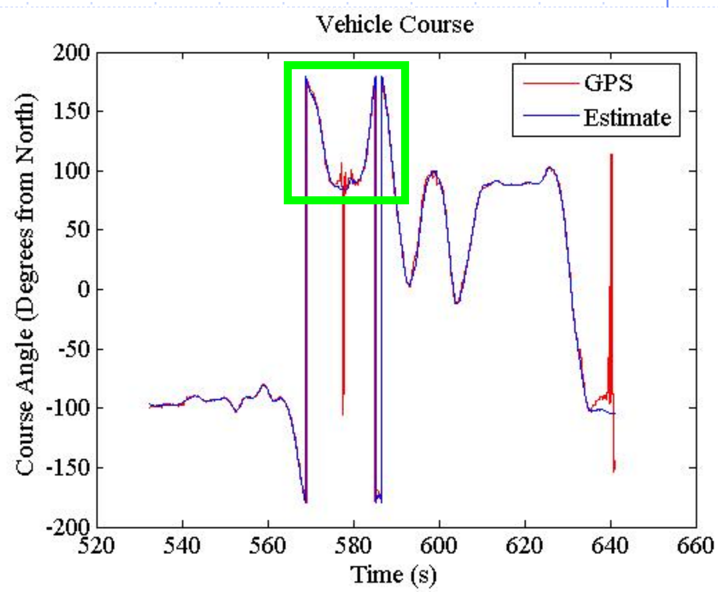
DARPA Grand Challenge (Overview)

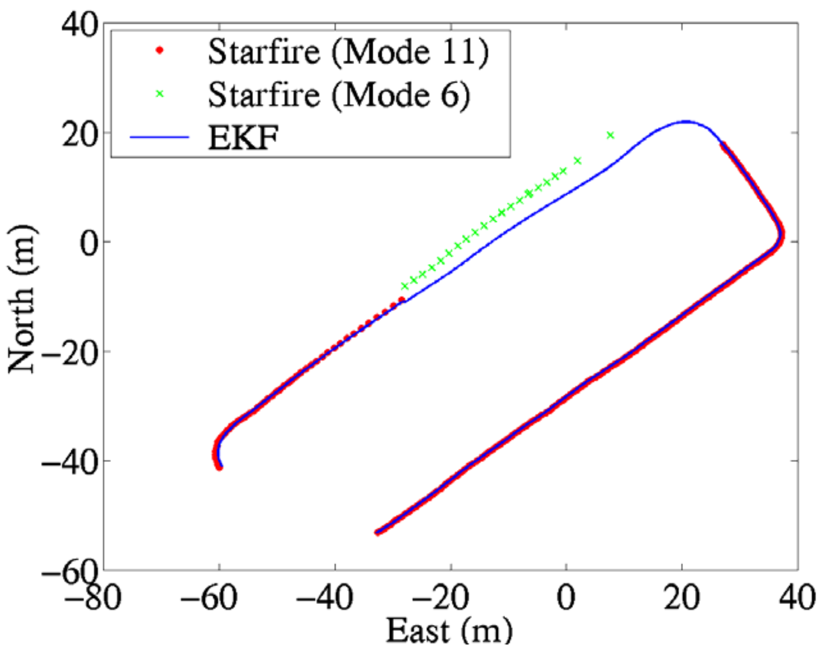
- Autonomous ground vehicle race in February 2004 and October 2005
- 130+ miles across desert terrain
- No human intervention
- Avoid obstacles in path while remaining in corridor
- Auburn University partnered with SciAutonics and Team Terramax

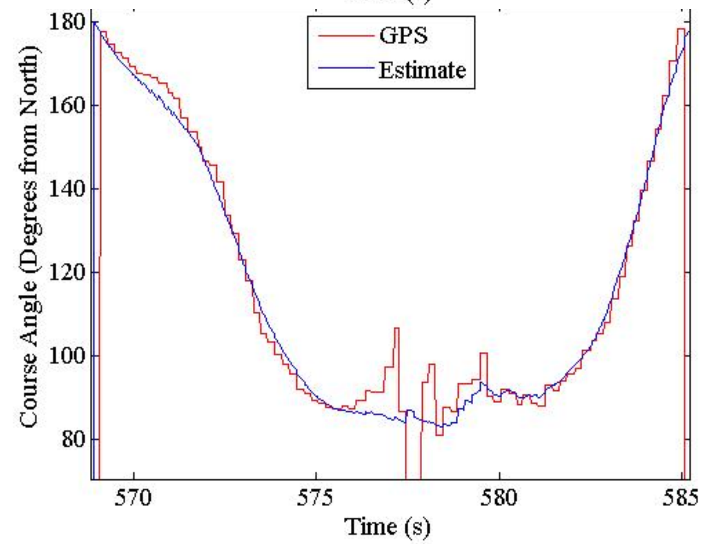
- 2004 race did not prove successful
  - Furthest competitor reached 7 out of 142 miles
- 2005 race demonstrated some capability of autonomous vehicles
  - Five teams finished race

Robust Navigation

- The system successfully tracked GPS measurements when they were available
- Bridged brief erroneous GPS measurements

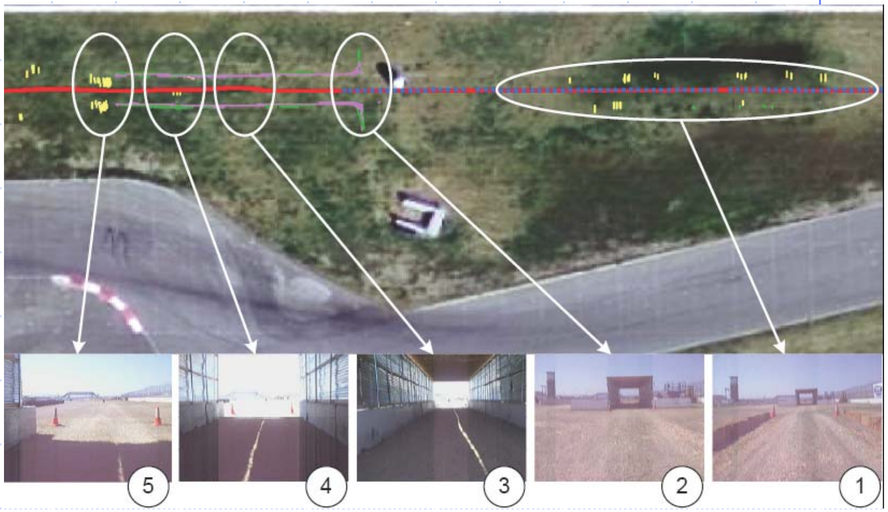






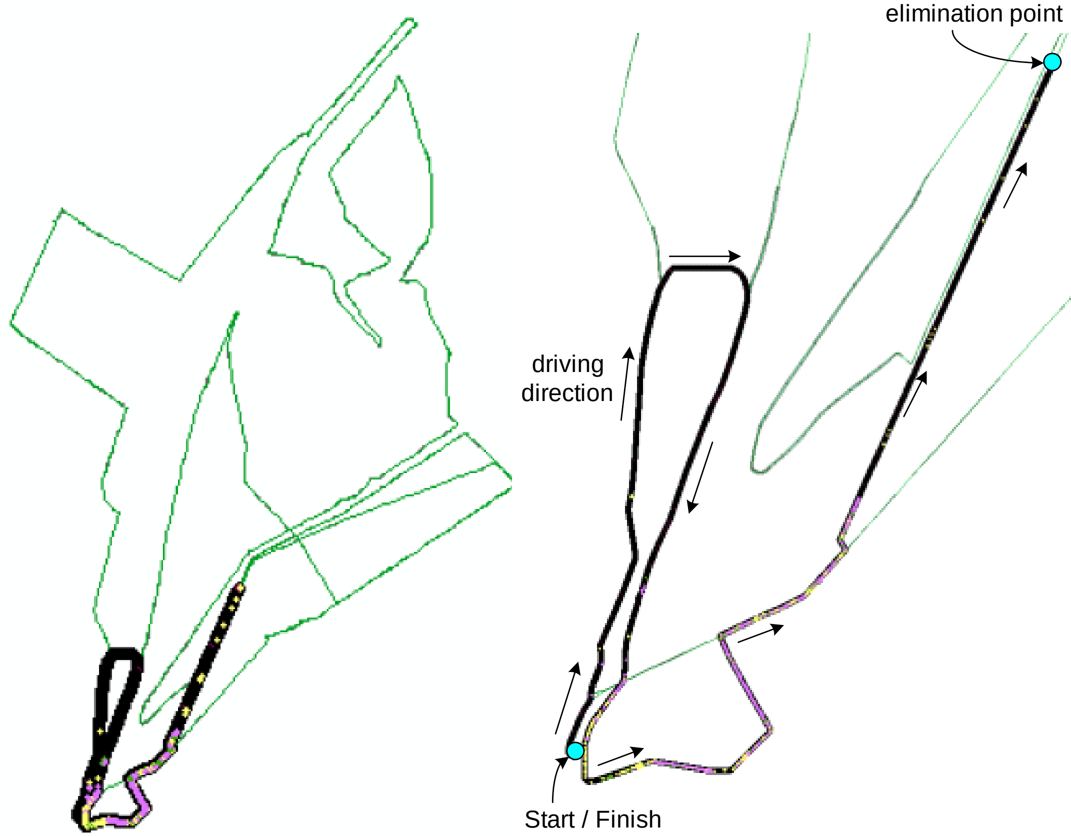
DARPA Grand Challenge
National Qualification Event

- Failed to finish first run because of GPS receiver malfunction
- Successfully completed next three runs
- One of ten cars granted early entry into DARPA Grand Challenge



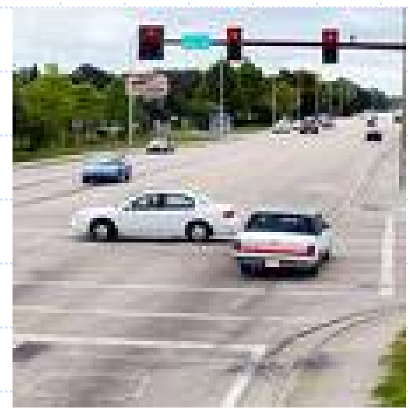
DARPA Grand Challenge 2005 Course

- Completed 16 miles before USB hub failed and crashed a computer
- Vehicle performed very well while on course



NEW DARPA Urban Challenge

- So now that you can make a vehicle drive from Kirkuk to Baghdad, can you make a vehicle that can drive through Baghdad?



- Must obey traffic laws and interact with other traffic
- City grid will be set aside and autonomous vehicle teams will interact in pursuit of “missions.”

Conclusions

- GPS is a great sensor
- GPS measurements can be used for control and estimation in farm vehicles
- GPS can be combined with low-cost inertial sensors to provide a high-update rate, low noise, bias free navigation solution
- Sensing ability of GPS will lead to many other advances in control and navigation of autonomous systems

Auburn University

GPS and Vehicle Dynamics Lab

http://gavlab.auburn.edu