An Experimental Exploration of Low-Cost Solutions for Precision Ground Vehicle Navigation

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Presentation Overview

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Motivation

- Autonomous vehicles are coming at some level
  - Safety
  - Transportation cost
- Cost is the greatest limiting factor for the consumer market
- What is the best way to assist navigation through production vehicle on-board sensors
  - **ESC**
    - **WSS and Steer Angle Sensors**
    - **IMU (partial)**
  - **Navigation**
    - **GPS**
  - ACC
    - Lidar/Radar
  - Lane Tracking
    - Camera

Prior Art - GPS/INS Aided by Odometry

- Ground Vehicles
  - Abbot, Powell, and Kubo
    - 1999 – Limiting INS error growth through WSS longitudinal vehicle velocity
  - Dissanayake
    - 2001 – WSS and 2 non-holonomic constraints
  - Gao
    - 2006 – WSS and 2 non-holonomic constraints (claims 90% vs GPS/INS)
    - 2007 – Detect when non-holonomic assumptions violated (claims 92% vs GPS/INS)
  - Li
    - 2010 – WSS and 2 non-holonomic constraints to derive 3-D velocity updates to aid 3-DOF IMU
  - Somieski
    - 2010 – Compared differential wheel speed vs **WSS/Gyro**
  - Hazlett
    - 2013 – EKF vs UKF using differential WSS measurements (simulation only)
  - Ryan
    - 2011 – Proves lateral non-holonomic constraint assumption fails, even at low dynamics

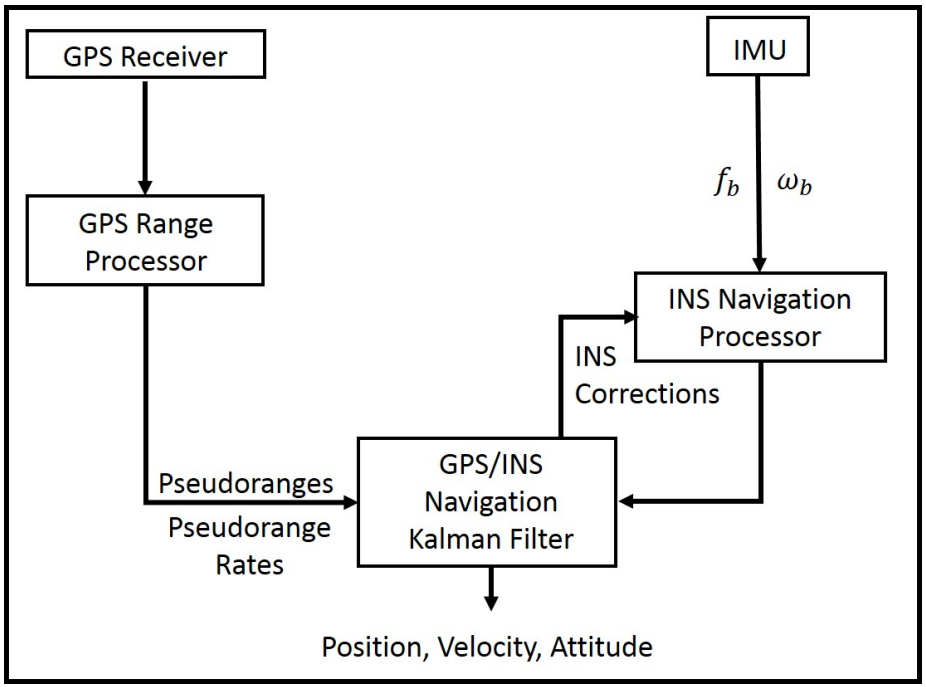
Prior Art - GPS/INS Aided by Vehicle Model

- Ground Vehicles
  - Bonnifait
    - 2003 – **Dynamic Model** vs Kinematic Model vs Differential WSS (no IMU)
  - Kochem and Betaille
    - 2002 – Dynamic Tricycle Model vs **WSS/Gyro(yaw) EKF** for parallel parking maneuvers (no GPS)
  - Ma
    - 2003 – GPS/INS/Kinematic Model compared heading solution Kinematic Model vs **IMU**
- Aerial Vehicles
  - Lie
    - 2013 – Low-fidelity aircraft dynamic model aid GPS/INS, eliminate pitot tube and AoA/ Sideslip vanes
  - Crocoll
    - 2013 – Unified Model Technique for INS aided by VDM in prediction step of EKF
  - Koifman and Bar-Itzhack
    - 1999 – Pseudo-Measurement Coupling for INS aided by VDM in prediction step of EKF (computationally intensive)

Traditional GPS/INS Approach

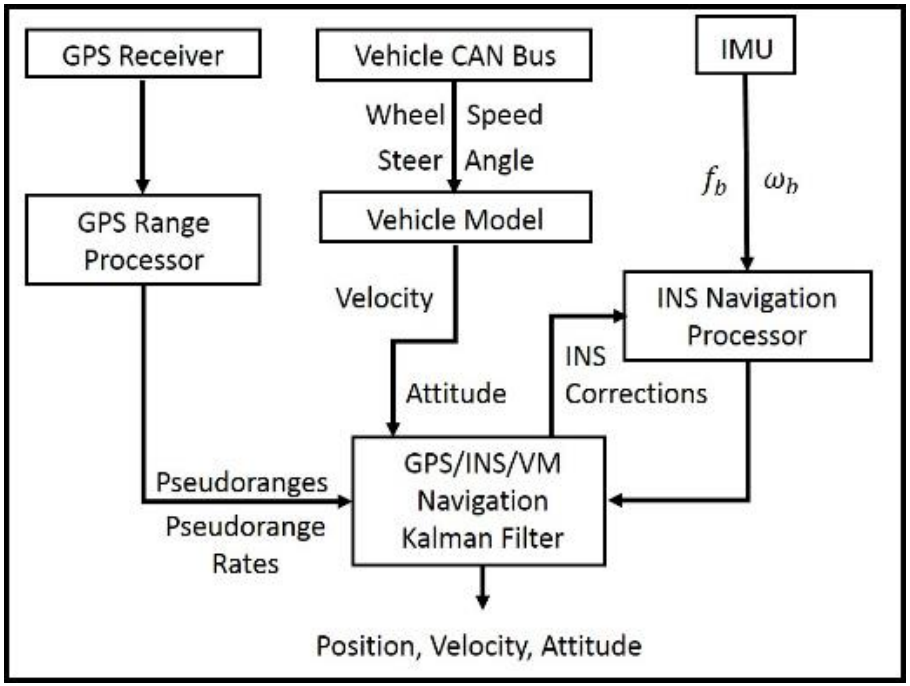
- Closely Coupled Extended Kalman Filter

$$X = \left[\delta P_e \;\; \delta V_e \;\; \delta \Psi \;\; b_a \;\; b_g \;\; b_{cerr} \;\; b_{cdft}\right]^{\mathrm{T}}$$



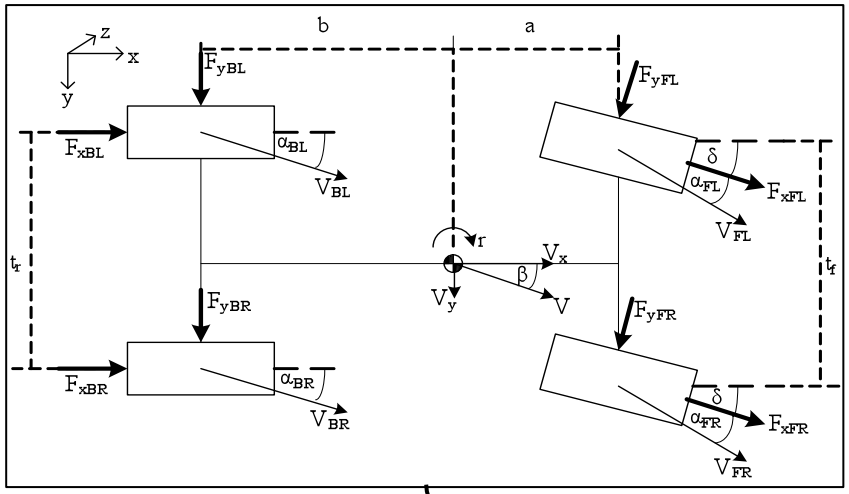
GPS/INS/VM Overview

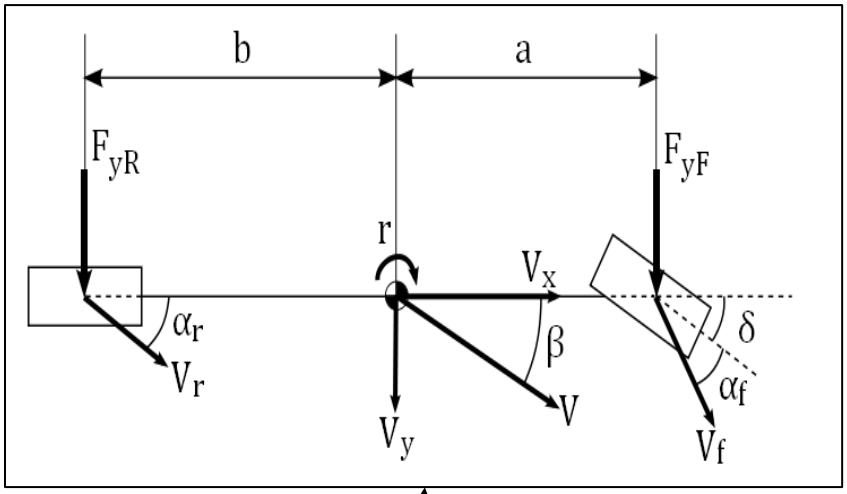
- What is the optimal method of inclusion for the Vehicle Model output into the navigation filter?



Vehicle Dynamic Model

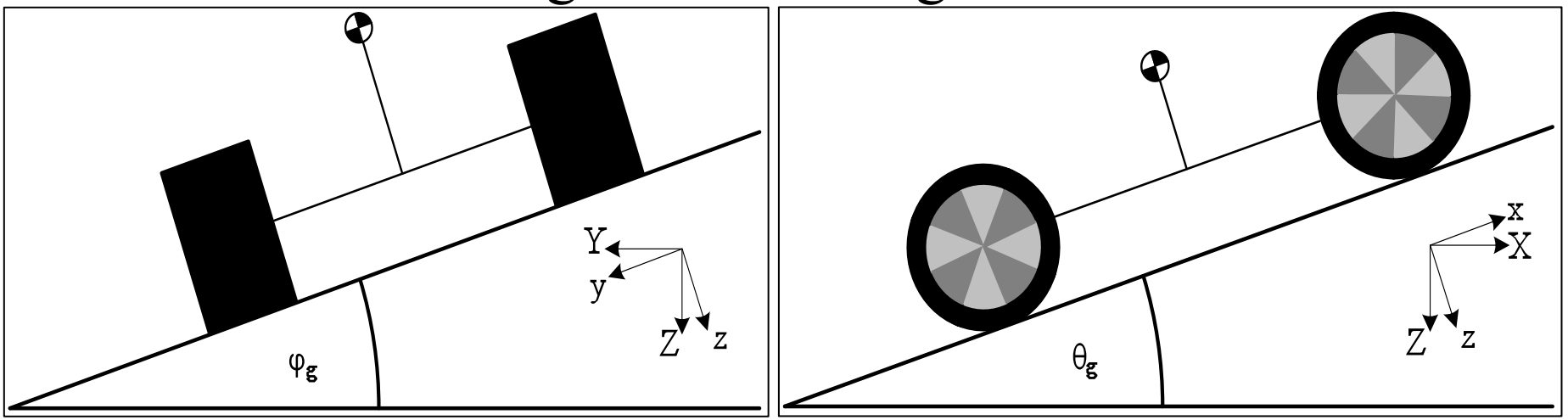
- 4 wheel to 2 wheel model
- Longitudinal tire force – linear model calculation based on longitudinal accelerations
- Lateral tire force – linear model $F = C_\alpha \alpha$





Vehicle Model Error Sources

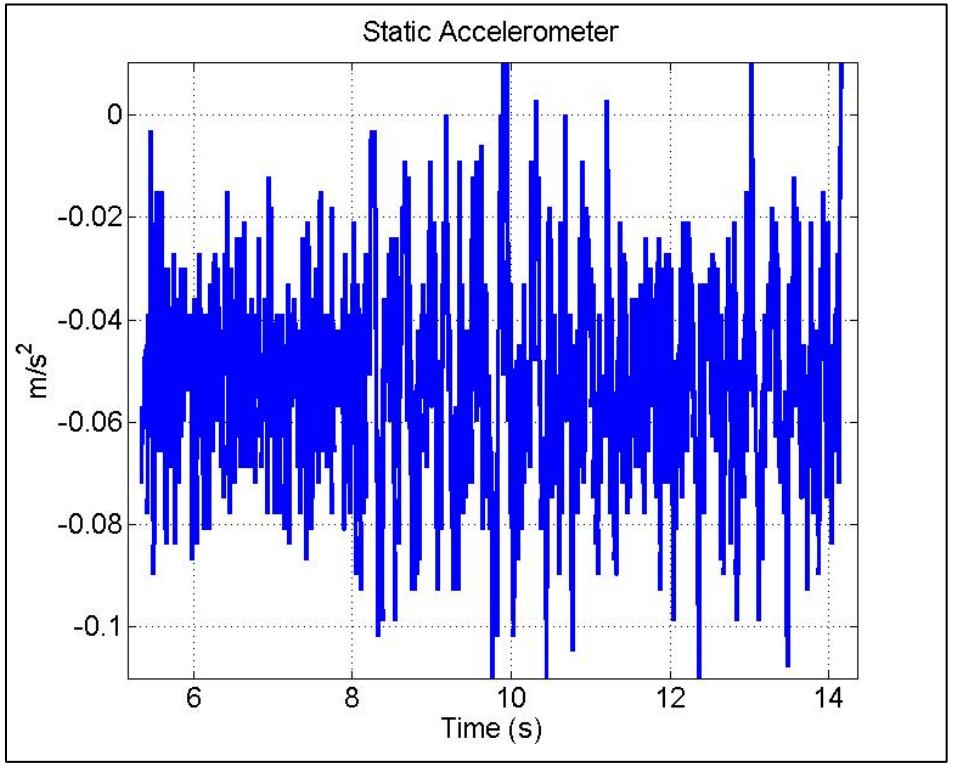
- Lateral and longitudinal road grade



- Lateral and longitudinal wheel slip
  - Worst case: sliding and/or spinout
  - Minor slip during any acceleration or braking scenario
- Linear model breaks down at high dynamics

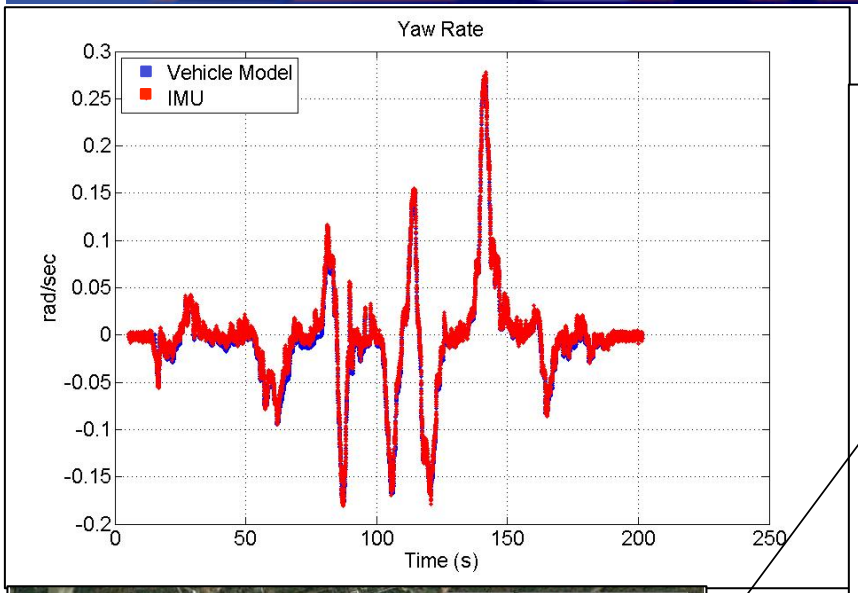
Low-Cost INS

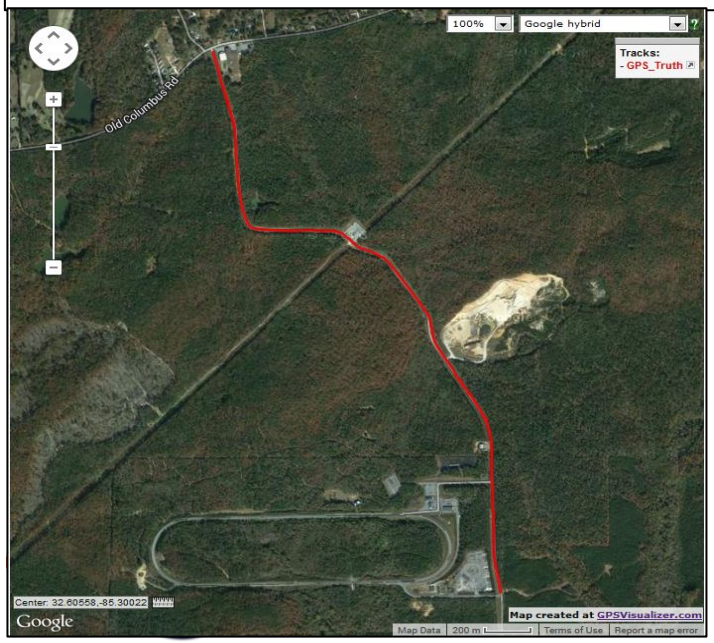
- Disadvantages
  - Biases
  - Scale factor and cross-coupling errors
  - Alignment errors
  - Random noise
  - Unknown roll and pitch (limited DOF)

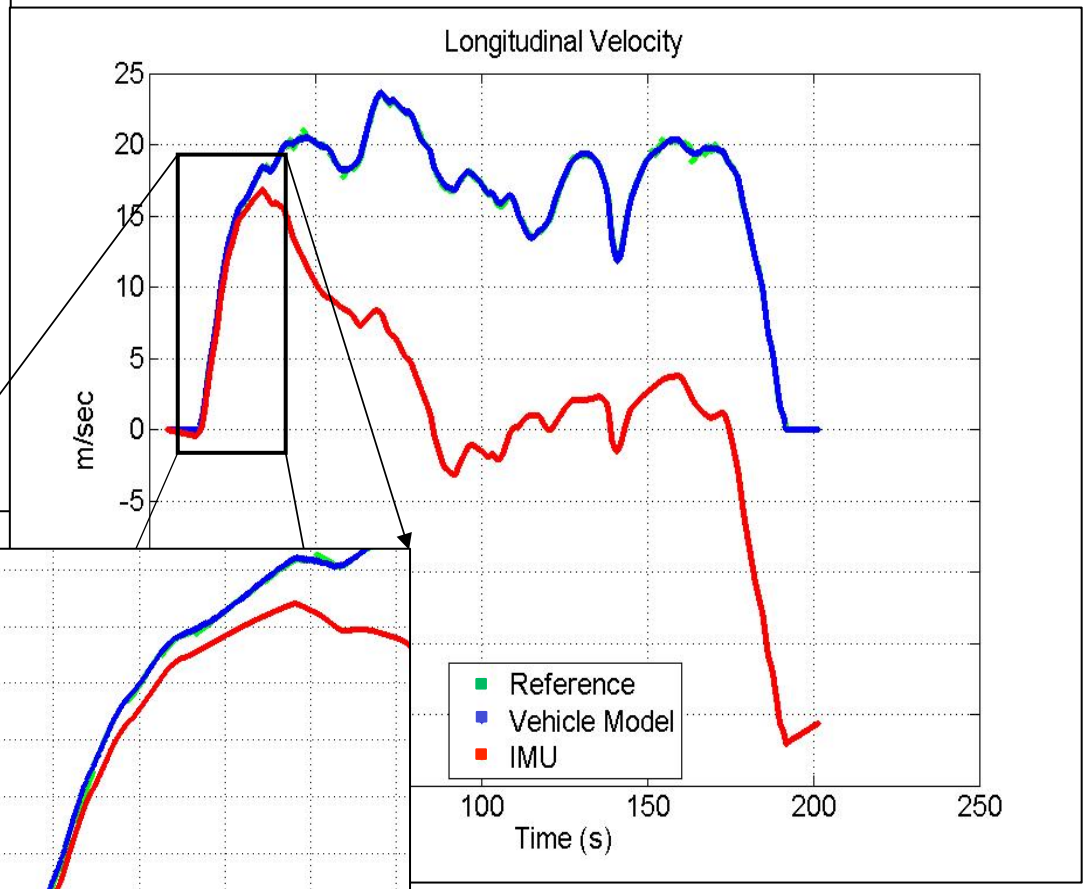


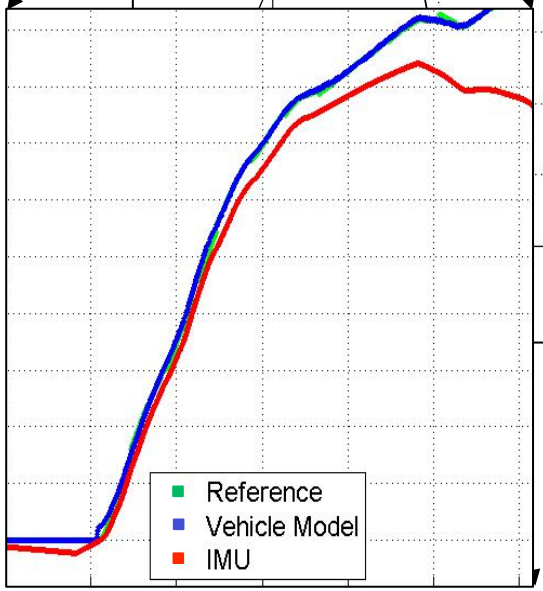
- Advantages
  - High bandwidth output
  - Invulnerable to outside interference
  - **Accuracy not affected by high dynamics**

Standalone INS and VM Comparison



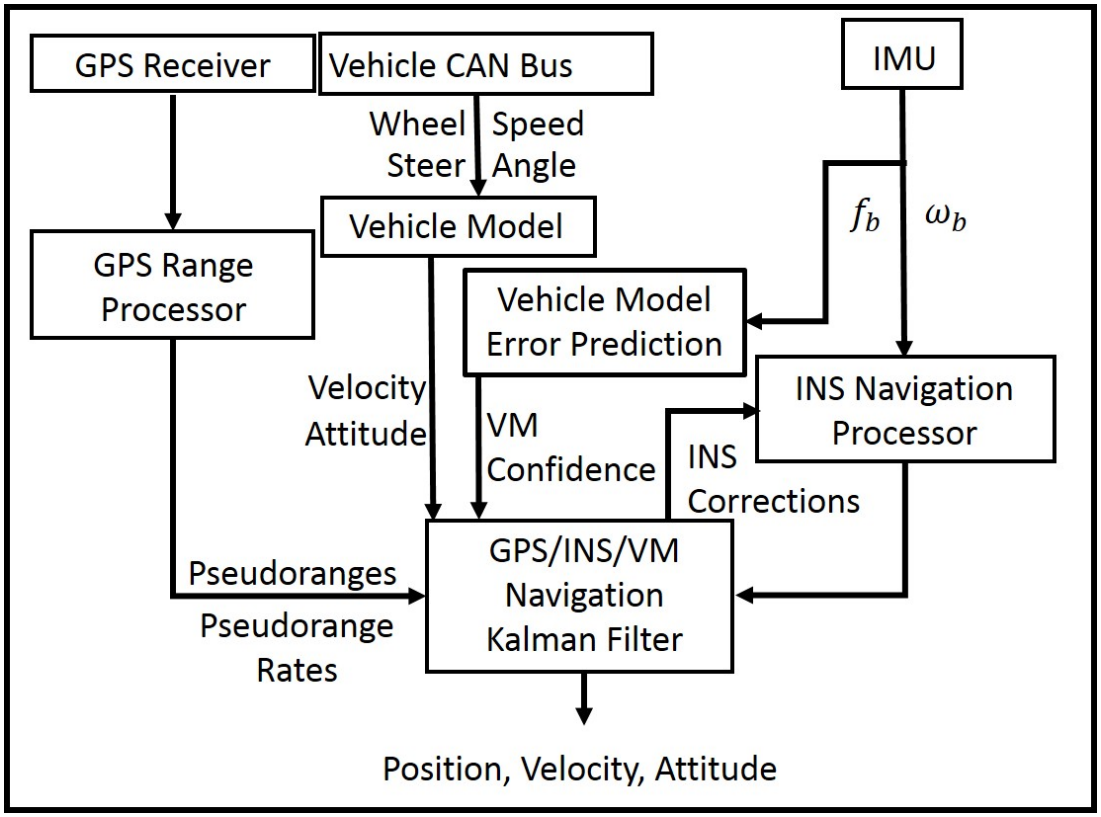






New VM Navigation Algorithm

- Measurement Update due to Vehicle Model's redundant nature to INS solution and ability to ignore VM solution during periods of low confidence
- Inertial Navigation Solution maintained through prediction update



Vehicle and Sensor Setup

- 2003 Infinity G35 Sedan

- Crossbow 400 MEMS IMU

- Novatel OEMstar Single Frequency GPS Receiver

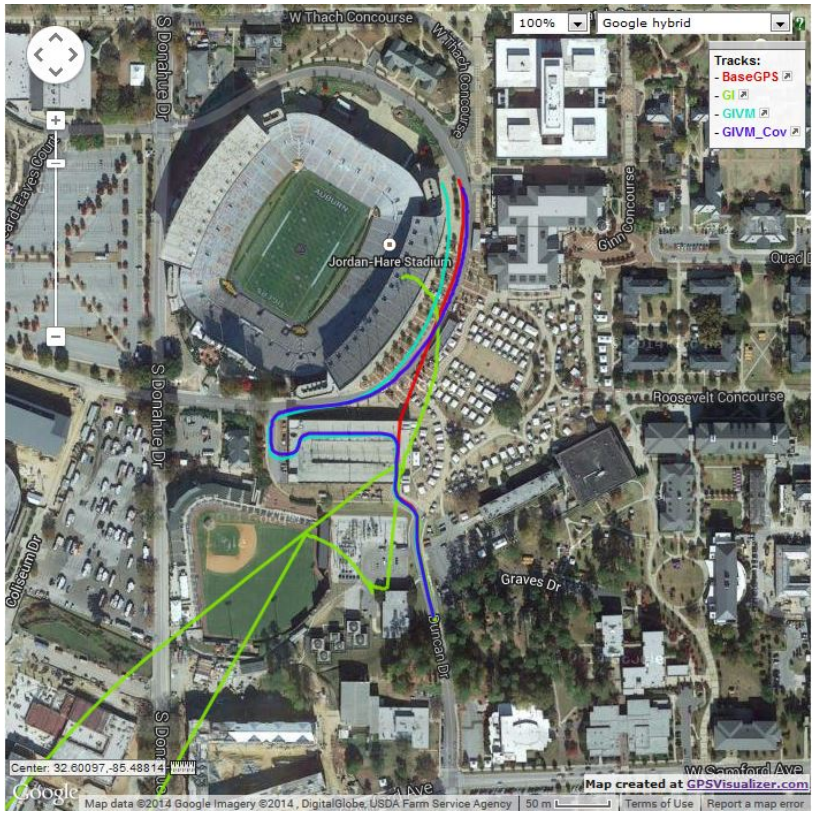
- Septentrio PolaRx2e Multi Antenna GPS Receiver

Data Collection Environment

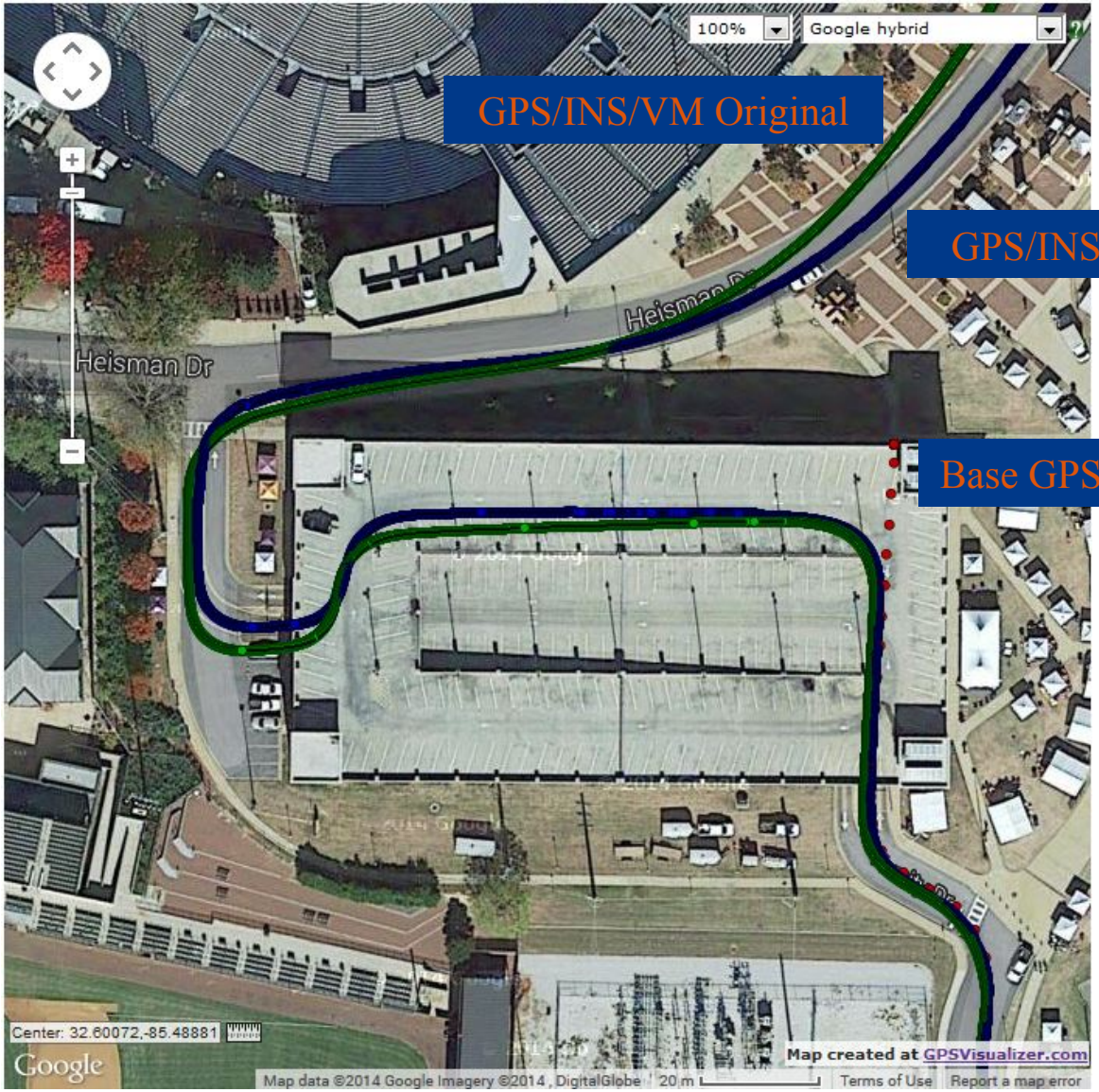
- Over 64 seconds of tracking less than 4 SV
- Vehicle maneuvers during GPS outage

Experimental Results

GIVM ~ GPS/INS/VM Original
GIVM_Cov ~ GPS/INS/VM New
GI ~ GPS/INS



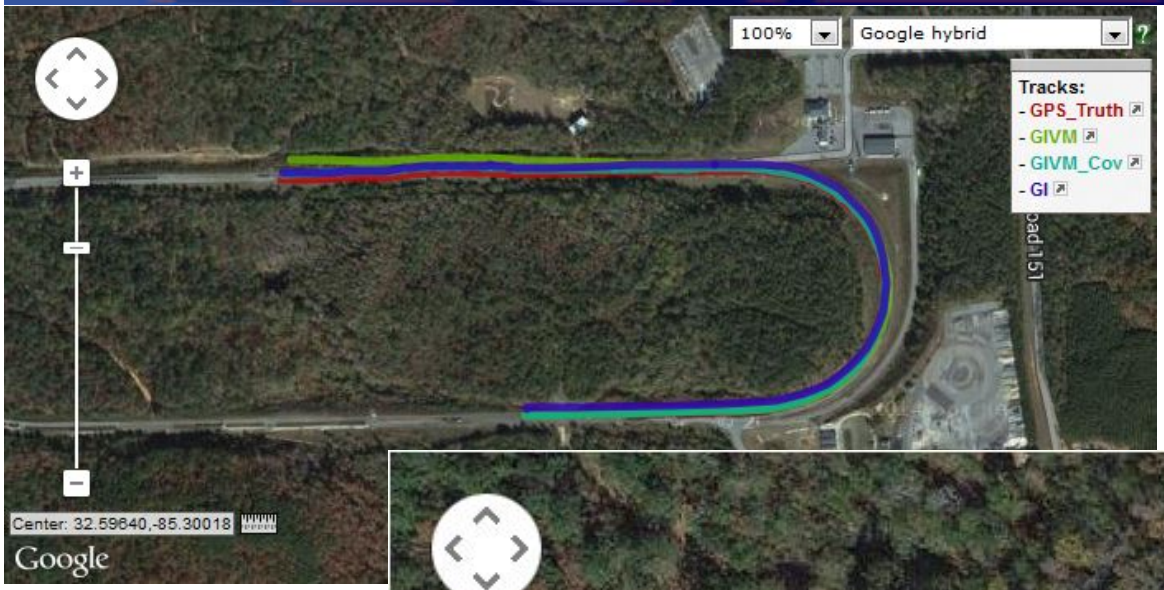
Experimental Results



Data Collection Environment

- 60 mph around 8 degree banked curve
- 54 mph double lane change maneuver

Experimental Results



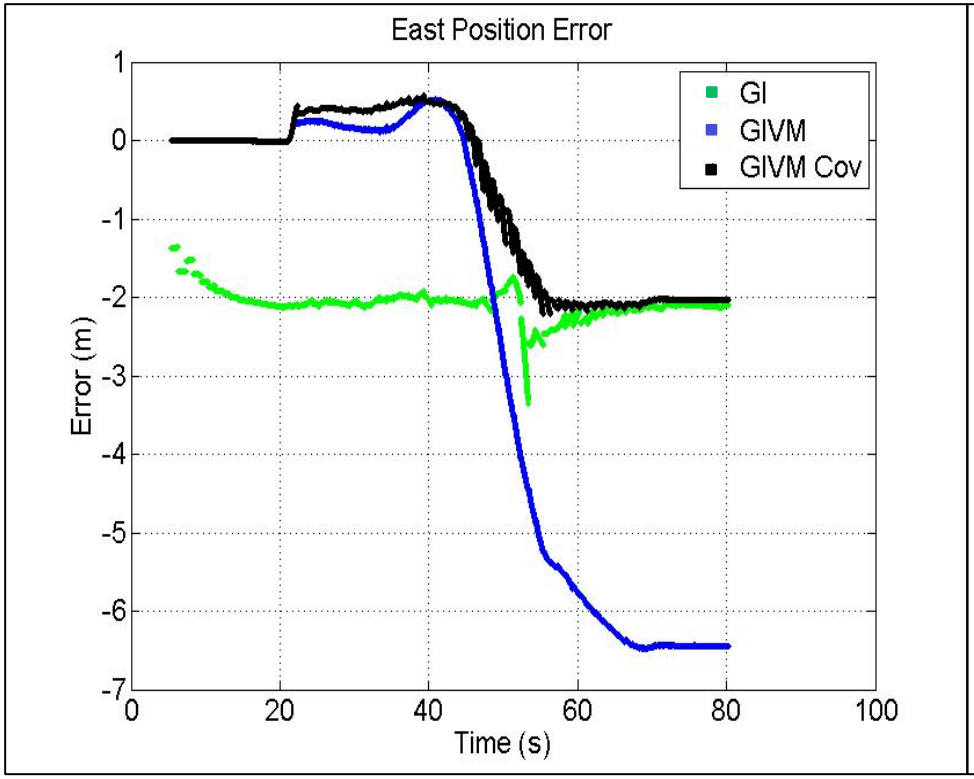
GIVM ~ GPS/INS/VM Original
GIVM_Cov ~ GPS/INS/VM New
GI ~ GPS/INS

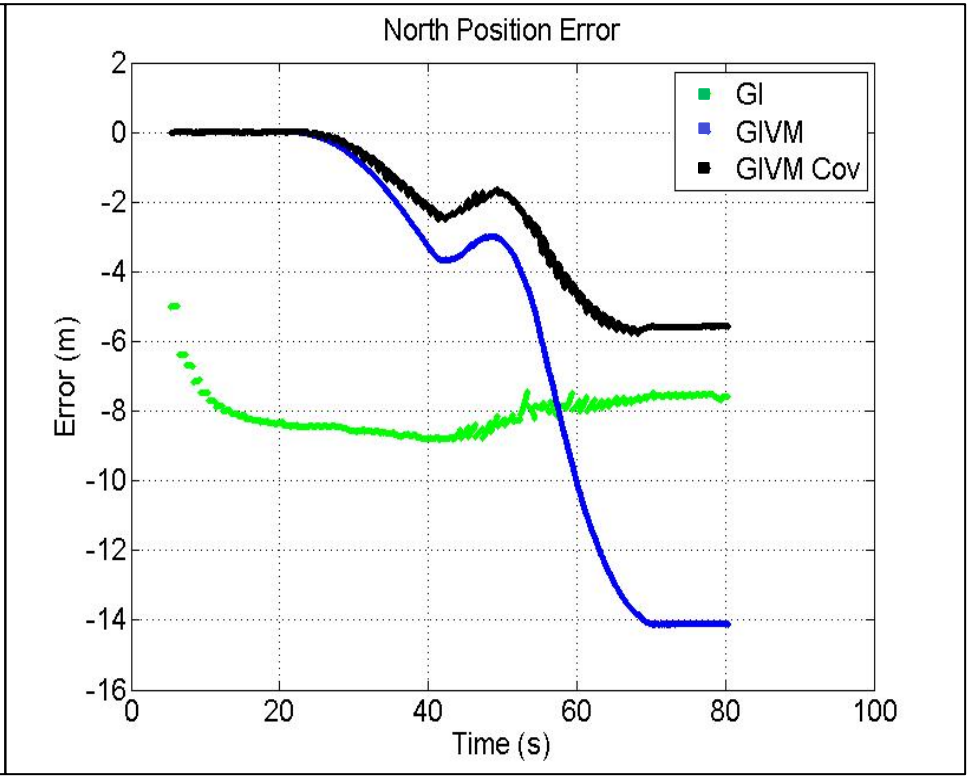
Data Collection Environment

- 66 mph around 8 degree banked curve

Experimental Results Error Analysis

GIVM ~ GPS/INS/VM Original
GIVM Cov ~ GPS/INS/VM New
GI ~ GPS/INS





Future Work

- Compare algorithms with 3 DOF IMU
- Examine corruption of A-priori wheel radius and steer angle ratio assumptions so that an estimate Wheel Speed and Steer Angle Bias is needed
- Research and compare further methods of using VM to assist GPS/INS (Stochastic Cloning and Unified Model Technique)
- Implement system in real time

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Questions