Use of Vision Sensors and Lane Maps to Aid GPS-INS under a Limited GPS Satellite Constellation

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John Allen

Work Funded by FHWA

Outline

- Prior Work/Contributions
- Motivation
- Background
- Lane Map
- 6DOF Filter Setup and Results
- Limited GPS Satellite Observabilty and Results

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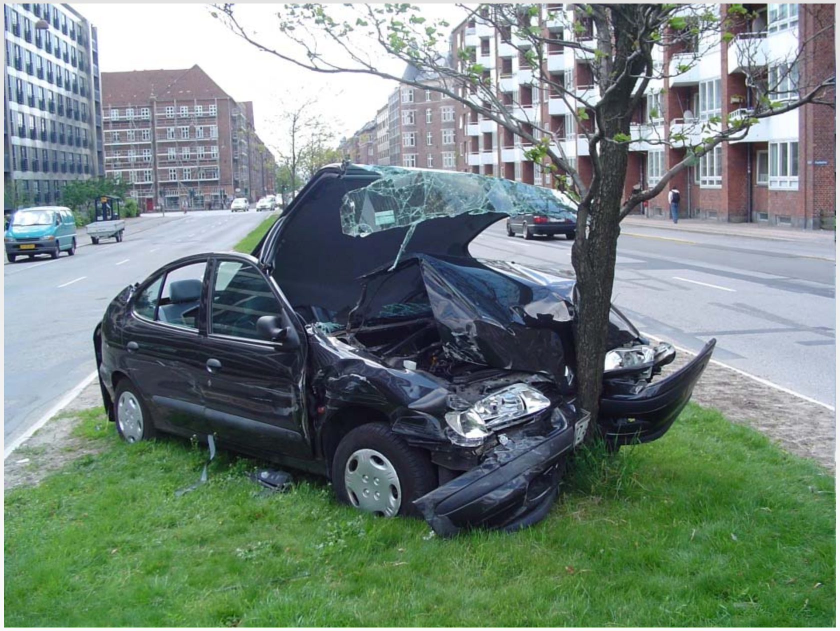
Motivation

- Research has shown that nearly half of traffic fatalities occur due to an unintentional lane departure.
  - Lane departure warning (LDW) systems may prevent many of these accidents.
  - Current LDW systems use only vision sensors.
- GPS based navigation filters are prone to failure in urban environments.
- Goal of this thesis is to present a method of combining vision measurements and vehicle constraints to maintain observability of a GPS based navigation filter when only 2 GPS satellites are visible.
- An Extended Kalman Filter is used to combine measurements from a GPS receiver, LiDAR, camera, and IMU.
  - The navigation coordinate frame used is a Cartesian coordinate frame based off a waypoint map.



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Prior Work

- J. Clanton, “Gps and inertial sensors enhancement for vision-based highway lane tracking," Master's thesis, Auburn University, 2006.
- S. Mammar, S. Glaser, and M. Netto, “Time to line crossing for lane departure avoidance: a theoretical study and an experimental setting," vol. 7, no. 2, pp. 226-241, 2006.
- J. Kibbel, W. Justus, and K. Furstenberg, “Lane estimation and departure warning using multilayer laserscanner," in Proc. IEEE Intelligent Transportation Systems, pp. 607-611, 2005.

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Contributions

- J. W. Allen and D. M. Bevly, “Use of vision sensors and lane maps to aid gps/ins under a limited gps satellite constellation," in 2010 ION GNSS Savannah, Georgia, 2010.
- J. W. Allen and D. M. Bevly, “Relating local vision measurements to global navigation satellite systems using waypoint based maps," in Proc. IEEE/ION Position Location and Navigation Symp. (PLANS), pp. 1204-1211, 2010.
- J. W. Allen, C. Rose, J. Britt, and D. M. Bevly, “Intelligent multi-sensor measurements to enhance vehicle navigation and safety systems," in 2009 International Technical Meeting. Anaheim, California, 2009.

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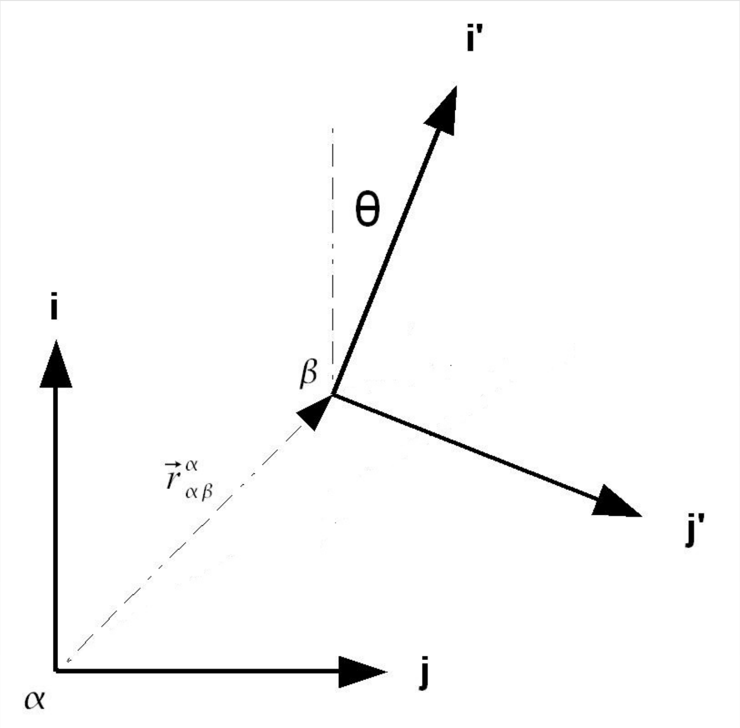
Background

- Typical navigation filter setup
  - Filter is based in a navigation coordinate frame
  - IMU measurements are given in the body coordinate frame and must be rotated into the navigation coordinate frame.
  - Update measurements are given in the navigation coordinate frame.
- Vision measurements are not given in the navigation coordinate frame.



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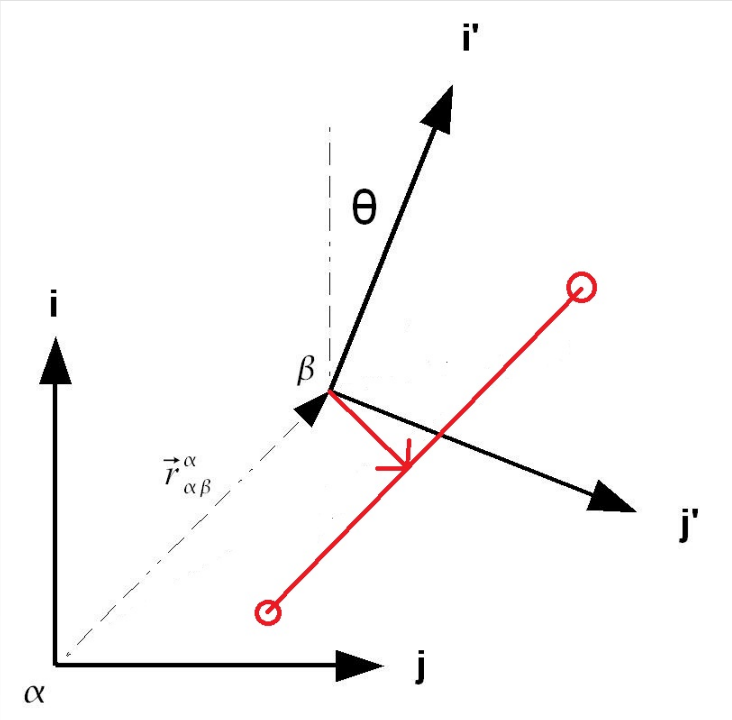
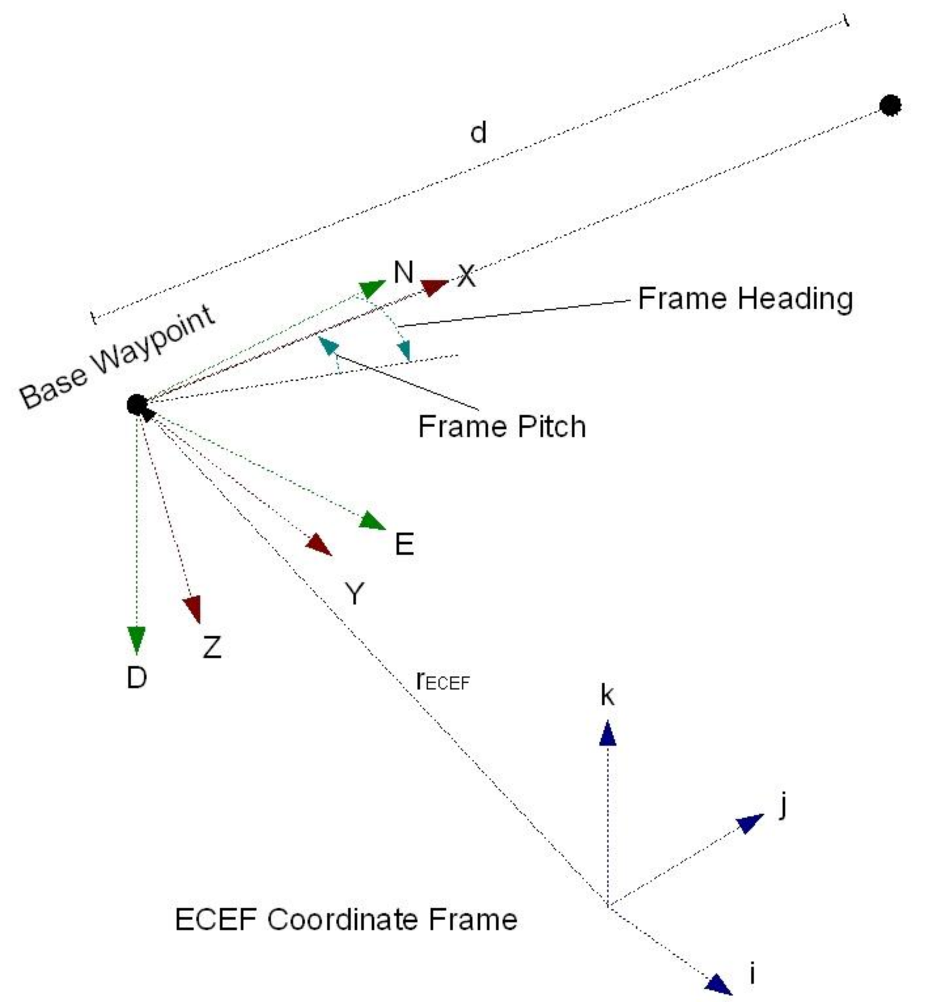
Background

- If measurements are not given in the navigation coordinate frame, they can be rotated and translated to the navigation coordinate frame.
- This will not work for a lane position measurement



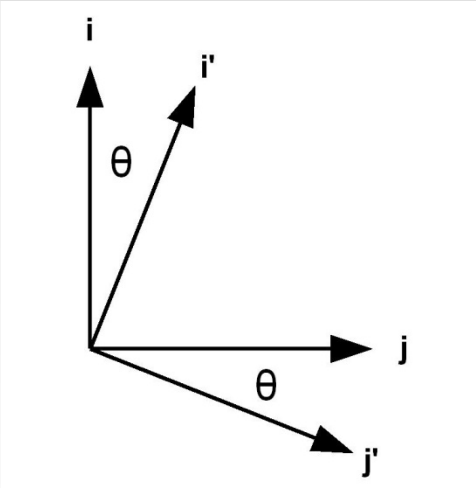
Background

- First approach was to construct a navigation filter with a navigation coordinate frame based on the way-point map.
- Ideally, we would like to add lane position measurements to typical types of navigation filters.



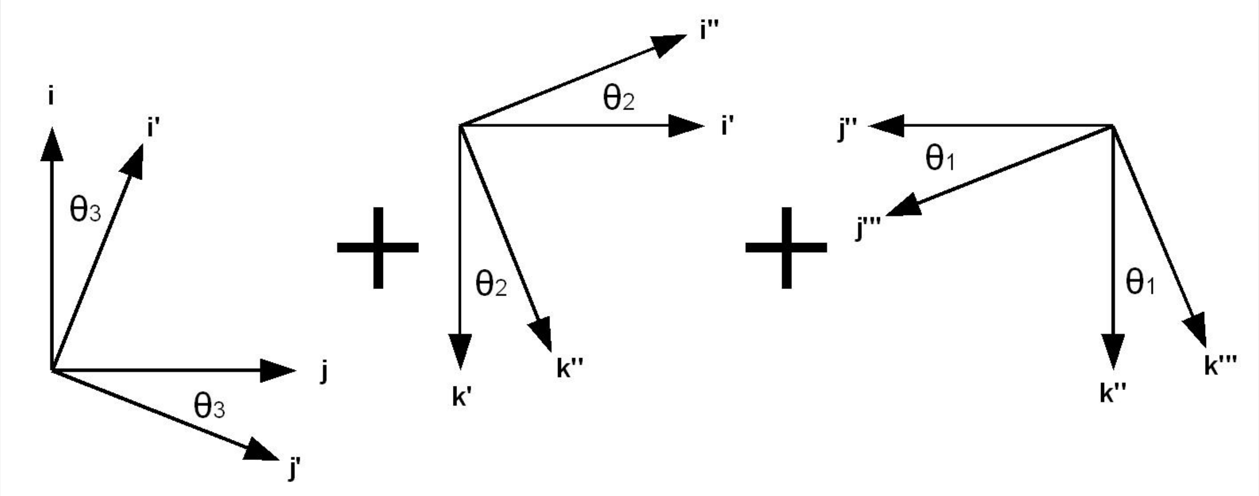
Rotation 2D

- 2D rotations are based on one rotation
- Rotation is about an axis that is perpendicular to the 2D coordinate frame



$$C_{(i,j)}^{(i',j')} = \begin{bmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{bmatrix}$$

Rotation 3D



$$C_{(i,j)}^{(i''',j''')} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & c_1 & s_1 \\ 0 & -s_1 & c_1 \end{bmatrix} \begin{bmatrix} c_2 & 0 & -s_2 \\ 0 & 1 & 0 \\ s_2 & 0 & c_2 \end{bmatrix} \begin{bmatrix} c_3 & s_3 & 0 \\ -s_3 & c_3 & 0 \\ 0 & 0 & 1 \end{bmatrix} = \begin{bmatrix} c_2 c_3 & c_2 s_3 & -s_2 \\ s_1 s_2 c_3 - c_1 s_3 & s_1 s_2 s_3 + c_1 c_3 & s_1 c_2 \\ c_1 s_2 c_3 + s_1 s_3 & c_1 s_2 s_3 - s_1 c_3 & c_1 c_2 \end{bmatrix}$$

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Rotation and Translation

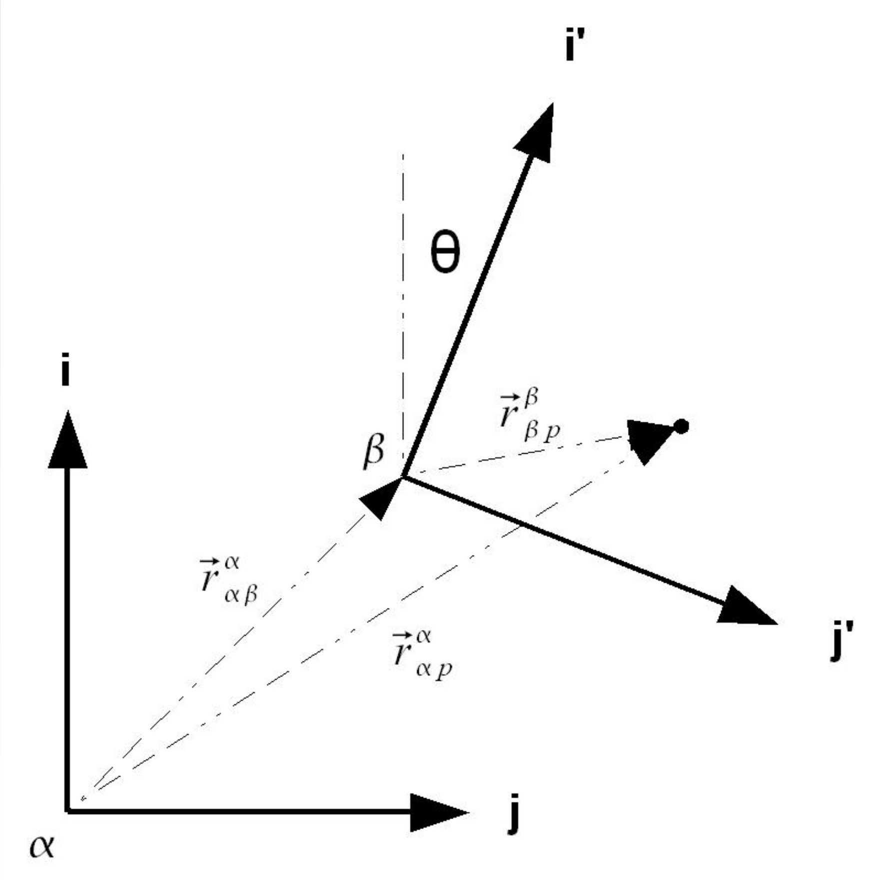
- Coordinates from 2 different coordinate frames can be mapped into each other.

$$\vec{r}^{\beta}_{\beta p} = C^{\beta}_{\alpha}\left[\vec{r}^{\alpha}_{\alpha p} - \vec{r}^{\alpha}_{\alpha\beta}\right]$$

$$\vec{r}^{\alpha}_{\alpha p} = C^{\alpha}_{\beta}\vec{r}^{\beta}_{\beta p} + \vec{r}^{\alpha}_{\alpha\beta}$$

$$\vec{v}^{\beta} = C^{\beta}_{\alpha}\vec{v}^{\alpha}$$

$$\vec{v}^{\alpha} = C^{\alpha}_{\beta}\vec{v}^{\beta}$$



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Track Survey

- In order to use GPS to measure lane position, an accurate map of the lane must constructed.
- For our project, we surveyed the NCAT test track in Opelika, AL.

Google Earth

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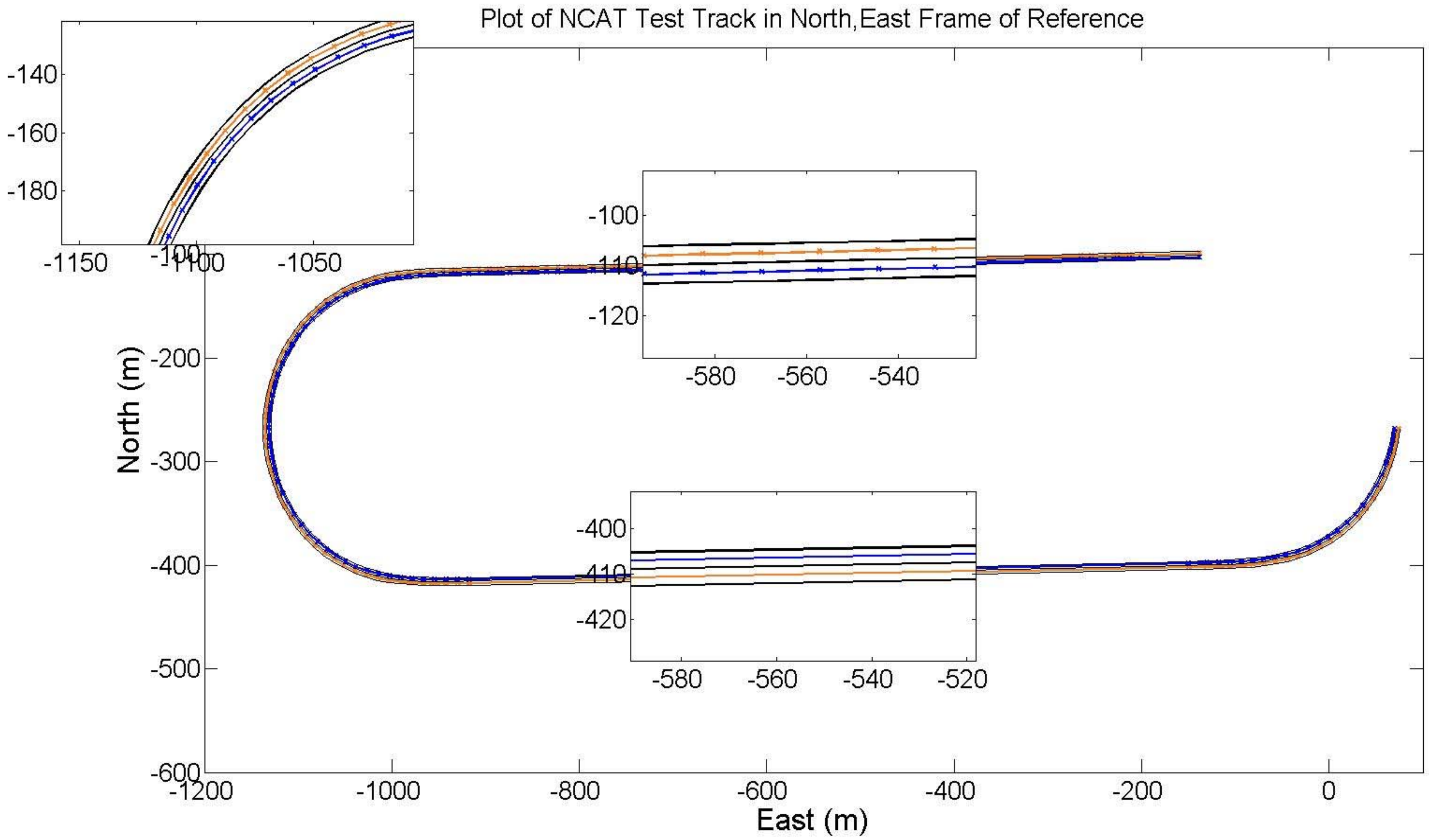
Track Survey

Track Map



Plot of NCAT Test Track in North,East Frame of Reference
North (m)
East (m)
-1200
-1000
-800
-600
-400
-200
0
-100
-200
-300
-400
-500
-600
-140
-160
-180
-1150
-1100
-1050
-100
-110
-120
-580
-560
-540
-400
-410
-420
-580
-560
-540
-520

Track Map

- RTK GPS used to survey the track
- RTK provides a very accurate base line between base station and rover
- Survey should be saved as base-line vectors from a marked location in order to prevent global biasing

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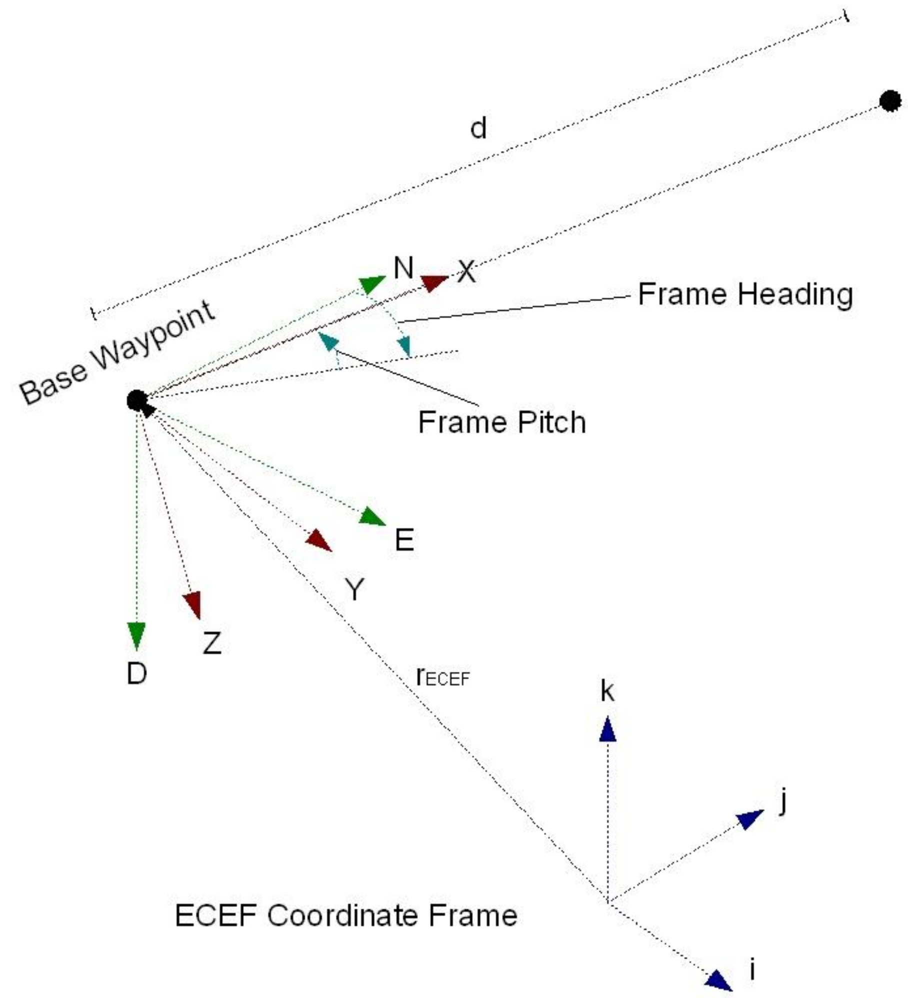
Track Map

- Along with waypoint positions, road attitude is needed
- Attitude represents rotation from the ECEF (navigation) coordinate frame to the Road (measurement) coordinate frame
- Road coordinate frame
  - X axis points in the from last waypoint passed to next waypoint
  - Y axis points right when facing direction of travel
  - Z axis points down with respect to the x-y plane



Track Map

- Can be thought of as 4 Euler rotations (longitude, latitude, road heading, and road pitch)
  - Longitude and Latitude can be determined from waypoint positions
  - Road heading and pitch can be determined by waypoint geometry.
- Wish to determine the 3 Euler angles that correspond to the 4 known rotations

$$Map\ Database = \begin{bmatrix} \vec{r}^{e}_{er,1} & \vec{\varphi}_1 & d_{r,1} \\ \vdots & \vdots & \vdots \\ \vec{r}^{e}_{er,m} & \vec{\varphi}_m & d_{r,m} \end{bmatrix}$$

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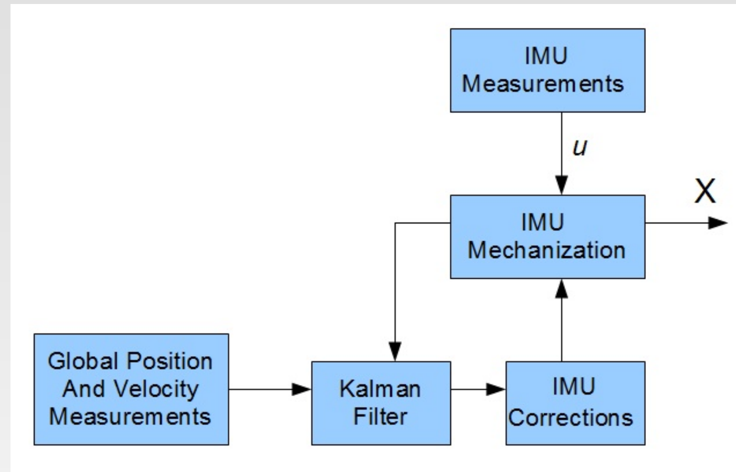
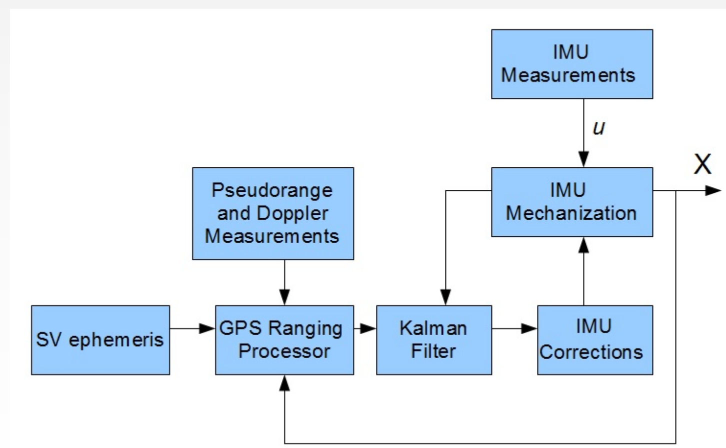
6 DOF Filter Setup

- States: position, velocity, attitude, accel/gyro biases, clock drift/bias
- Navigation coordinate frame is the global (ECEF) coordinate frame
- GPS measurements are given in the global coordinate frame

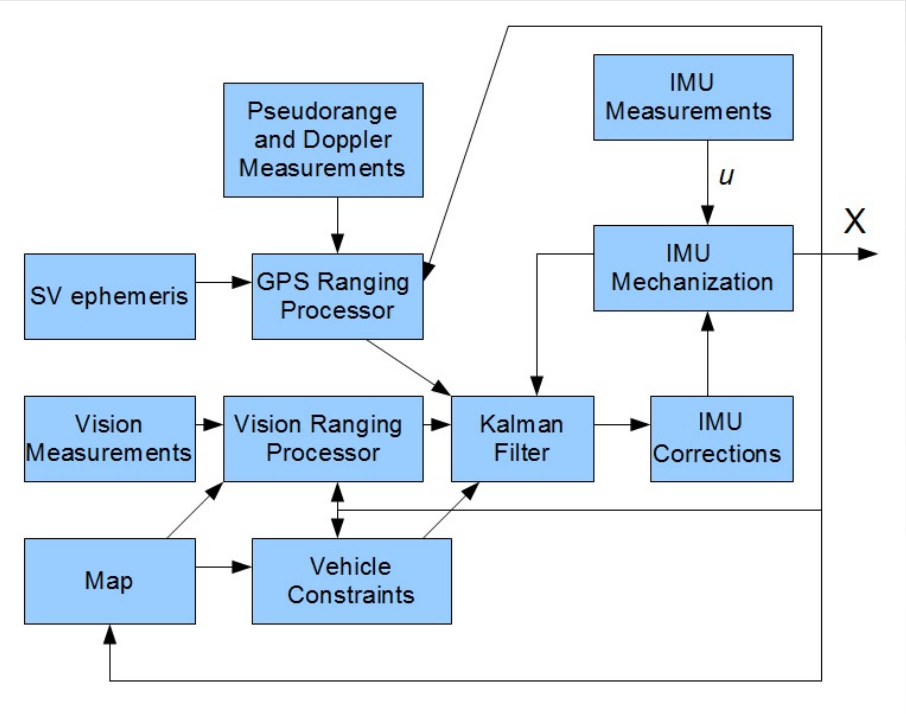
$$x = \left[\vec{r}^{\,e}_{eb} \quad \vec{v}^{\,e}_{eb} \quad \vec{a} \quad \vec{b}_f \quad \vec{b}_g \quad c\delta t \quad c\dot{\delta t}\right]^T$$





6 DOF Filter Setup

- Adding lane map results in the ability to use measurements in the road coordinate frame
    - Vision is used to measure position in one axis
    - Height above the road is constant allowing measurement of position in another axis



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Vision\Height Measurement Update

$$Map\ Database = \begin{bmatrix} \vec{r}^{\,e}_{er,1} & \vec{\varphi}_1 & d_{r,1} \\ \vdots & \vdots & \vdots \\ \vec{r}^{\,e}_{er,m} & \vec{\varphi}_m & d_{r,m} \end{bmatrix}$$

$$C_e^r = \begin{bmatrix} c_2c_3 & c_2s_3 & -s_2 \\ s_1s_2c_3 - c_1s_3 & s_1s_2s_3 + c_1c_3 & s_1c_2 \\ c_1s_2c_3 + s_1s_3 & c_1s_2s_3 - s_1c_3 & c_1c_2 \end{bmatrix}$$

$$\begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix} = C_e^r\left[\vec{r}^{\,e}_{eb} - \vec{r}^{\,e}_{er,i}\right]$$

$$h(x) = \begin{bmatrix} \hat{y} \\ \hat{h} \end{bmatrix} = \begin{bmatrix} C^r_{e\,(2,1)}\left(\vec{r}^{\,e}_{eb,1} - \vec{r}^{\,e}_{er,i,1}\right) + C^r_{e\,(2,2)}\left(\vec{r}^{\,e}_{eb,2} - \vec{r}^{\,e}_{er,i,2}\right) + C^r_{e\,(2,3)}\left(\vec{r}^{\,e}_{eb,3} - \vec{r}^{\,e}_{er,i,3}\right) \\ -C^r_{e\,(3,1)}\left(\vec{r}^{\,e}_{eb,1} - \vec{r}^{\,e}_{er,i,1}\right) - C^r_{e\,(3,2)}\left(\vec{r}^{\,e}_{eb,2} - \vec{r}^{\,e}_{er,i,2}\right) - C^r_{e\,(3,3)}\left(\vec{r}^{\,e}_{eb,3} - \vec{r}^{\,e}_{er,i,3}\right) \end{bmatrix}$$

$$e_1 = \left[C^r_{e\,(2,1)}, C^r_{e\,(2,2)}, C^r_{e\,(2,3)}\right]$$

$$e_2 = \left[-C^r_{e\,(3,1)}, -C^r_{e\,(3,2)}, -C^r_{e\,(3,3)}\right]$$

$$H(x) = \begin{bmatrix} e_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ e_2 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Vision\Height Measurement Update

$$Map\ Database = \begin{bmatrix} \vec{r}^{\,e}_{er,1} & \vec{\varphi}_1 & d_{r,1} \\ \vdots & \vdots & \vdots \\ \vec{r}^{\,e}_{er,m} & \vec{\varphi}_m & d_{r,m} \end{bmatrix}$$

$$C^r_e = \begin{bmatrix} c_2c_3 & c_2s_3 & -s_2 \\ s_1s_2c_3 - c_1s_3 & s_1s_2s_3 + c_1c_3 & s_1c_2 \\ c_1s_2c_3 + s_1s_3 & c_1s_2s_3 - s_1c_3 & c_1c_2 \end{bmatrix}$$

$$\begin{bmatrix} \hat{x} \\ \hat{y} \\ \hat{z} \end{bmatrix} = C^r_e\left[\vec{r}^{\,e}_{eb} - \vec{r}^{\,e}_{er,i}\right]$$

$$h(x) = \begin{bmatrix} \hat{y} \\ \hat{h} \end{bmatrix} = \begin{bmatrix} C^r_{e\,(2,1)}\left(\vec{r}^{\,e}_{eb,1} - \vec{r}^{\,e}_{er,i,1}\right) + C^r_{e\,(2,2)}\left(\vec{r}^{\,e}_{eb,2} - \vec{r}^{\,e}_{er,i,2}\right) + C^r_{e\,(2,3)}\left(\vec{r}^{\,e}_{eb,3} - \vec{r}^{\,e}_{er,i,3}\right) \\ -C^r_{e\,(3,1)}\left(\vec{r}^{\,e}_{eb,1} - \vec{r}^{\,e}_{er,i,1}\right) - C^r_{e\,(3,2)}\left(\vec{r}^{\,e}_{eb,2} - \vec{r}^{\,e}_{er,i,2}\right) - C^r_{e\,(3,3)}\left(\vec{r}^{\,e}_{eb,3} - \vec{r}^{\,e}_{er,i,3}\right) \end{bmatrix}$$

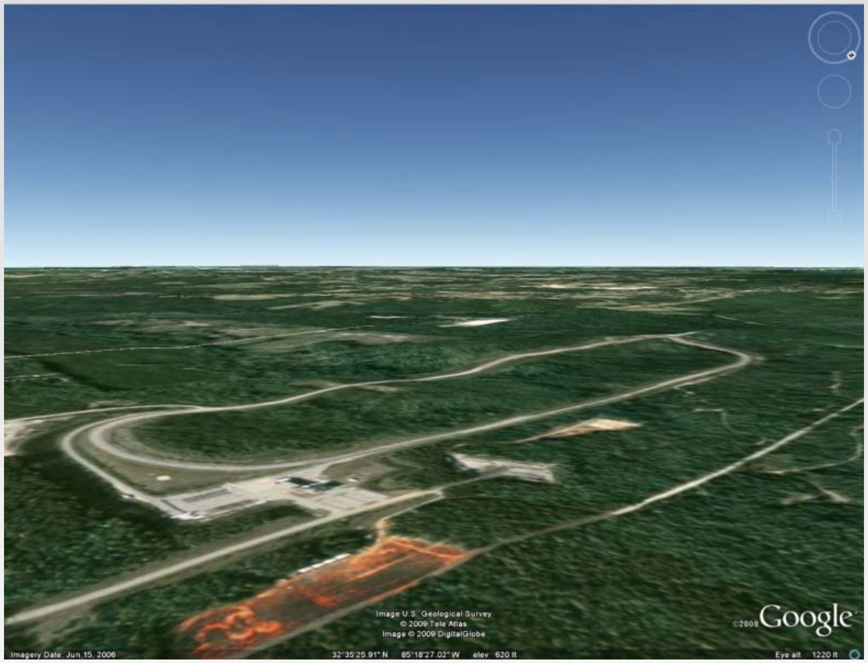
$$e_1 = \left[C^r_{e\,(2,1)}, C^r_{e\,(2,2)}, C^r_{e\,(2,3)}\right]$$

$$e_2 = \left[-C^r_{e\,(3,1)}, -C^r_{e\,(3,2)}, -C^r_{e\,(3,3)}\right]$$

$$H(x) = \begin{bmatrix} e_1 & 0 & 0 & 0 & 0 & 0 & 0 \\ e_2 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Test Setup

- All test was done at the Nation Center for Asphalt Testing (NCAT) test track in Opelika, AL
  - 2 Lanes
  - 1.8 mile oval
  - 8 degrees of bank in the turns



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Test Setup

- Results obtained by post processing real data.
- All data was collected at the NCAT test track
- Equipment Used:
  - Septentrio GPS receiver
  - Crossbow 440 IMU
  - IBEO ALASCA XT laser scanner
  - Logitch QuickCam Pro 9000

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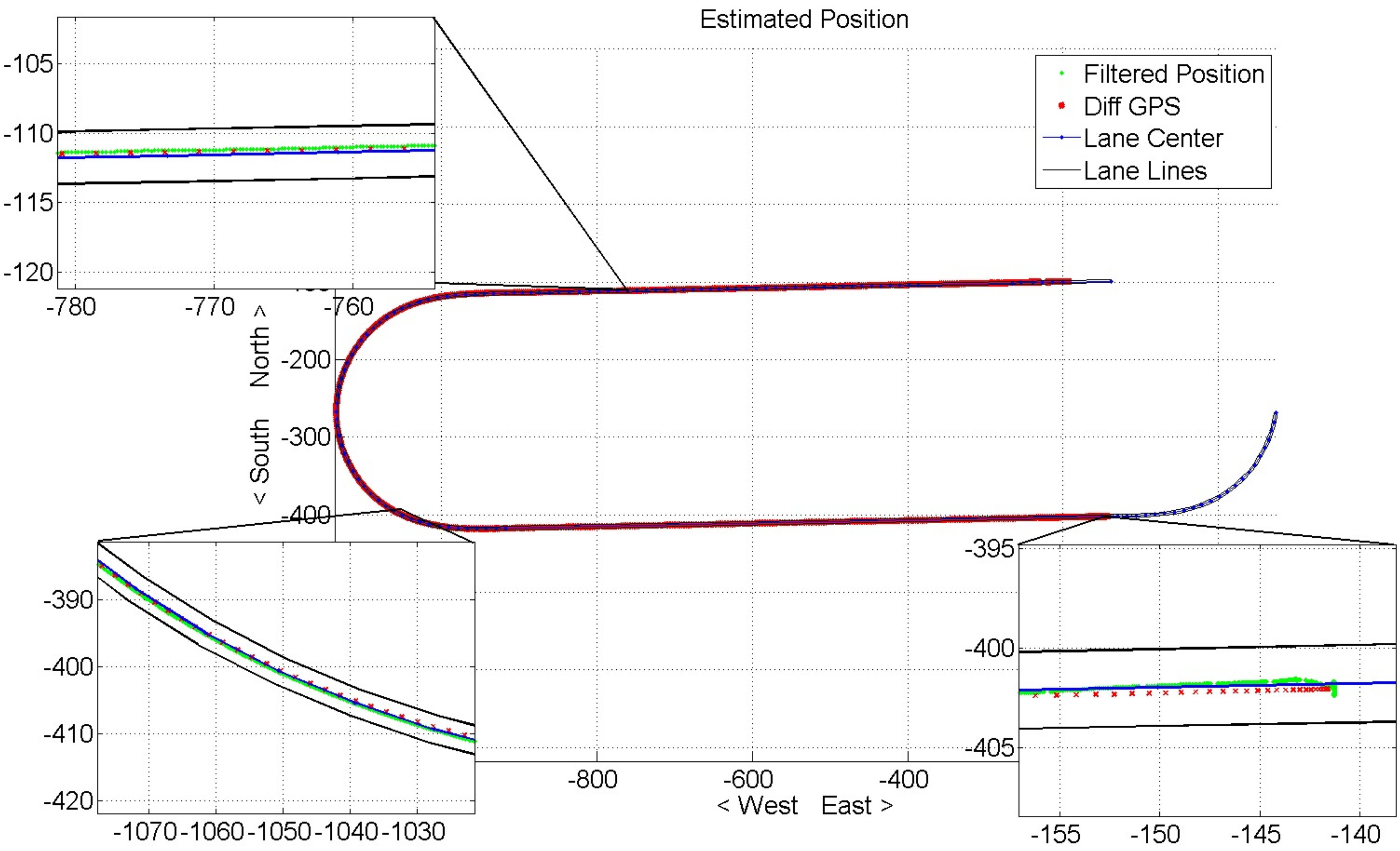
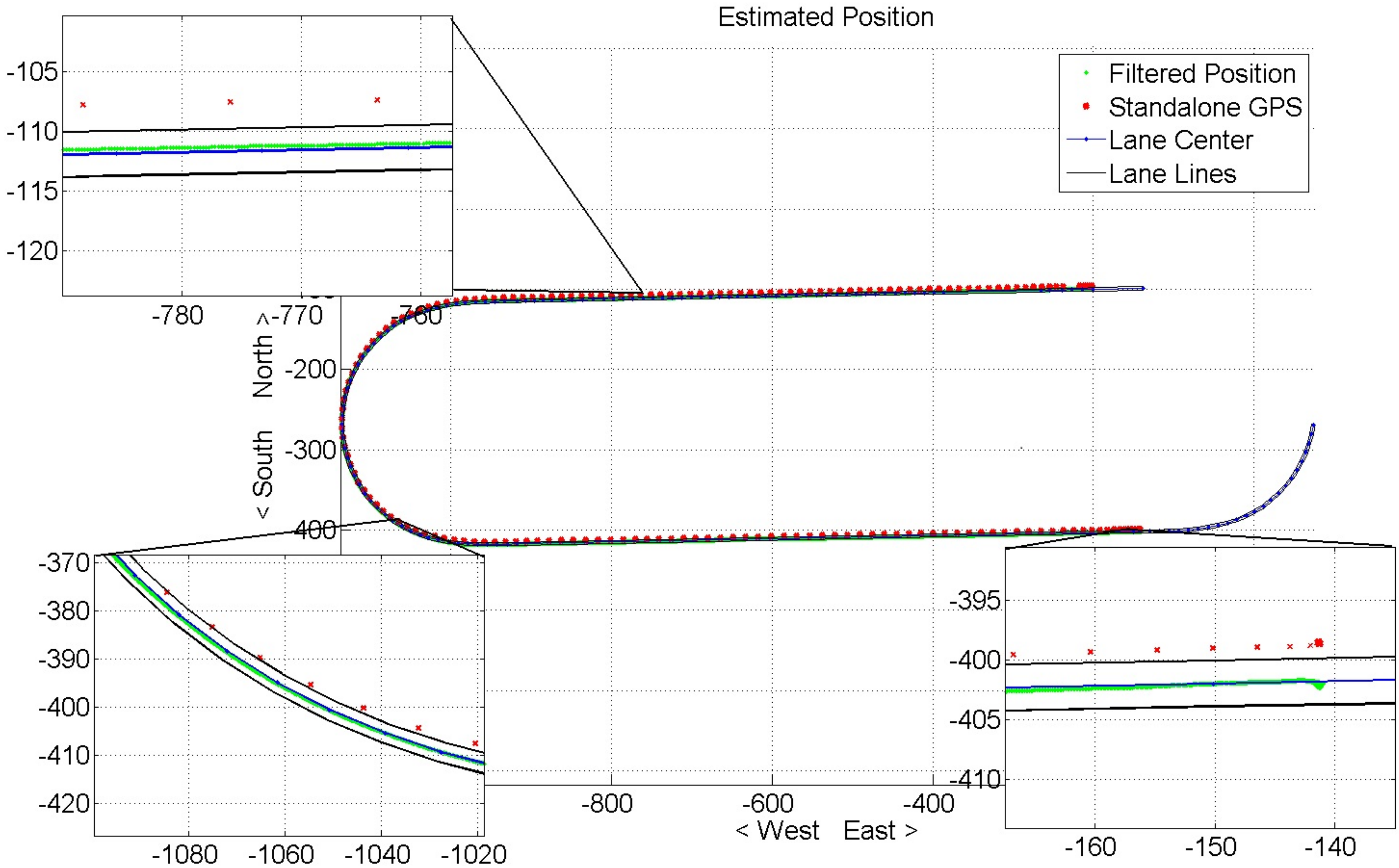
Results



Estimated Position
Filtered Position
Diff GPS
Lane Center
Lane Lines
< South North >
< West East >
-200
-300
-400
-800
-600
-400
-105
-110
-115
-120
-780
-770
-760
-390
-400
-410
-420
-1070 -1060 -1050 -1040 -1030
-395
-400
-405
-155
-150
-145
-140

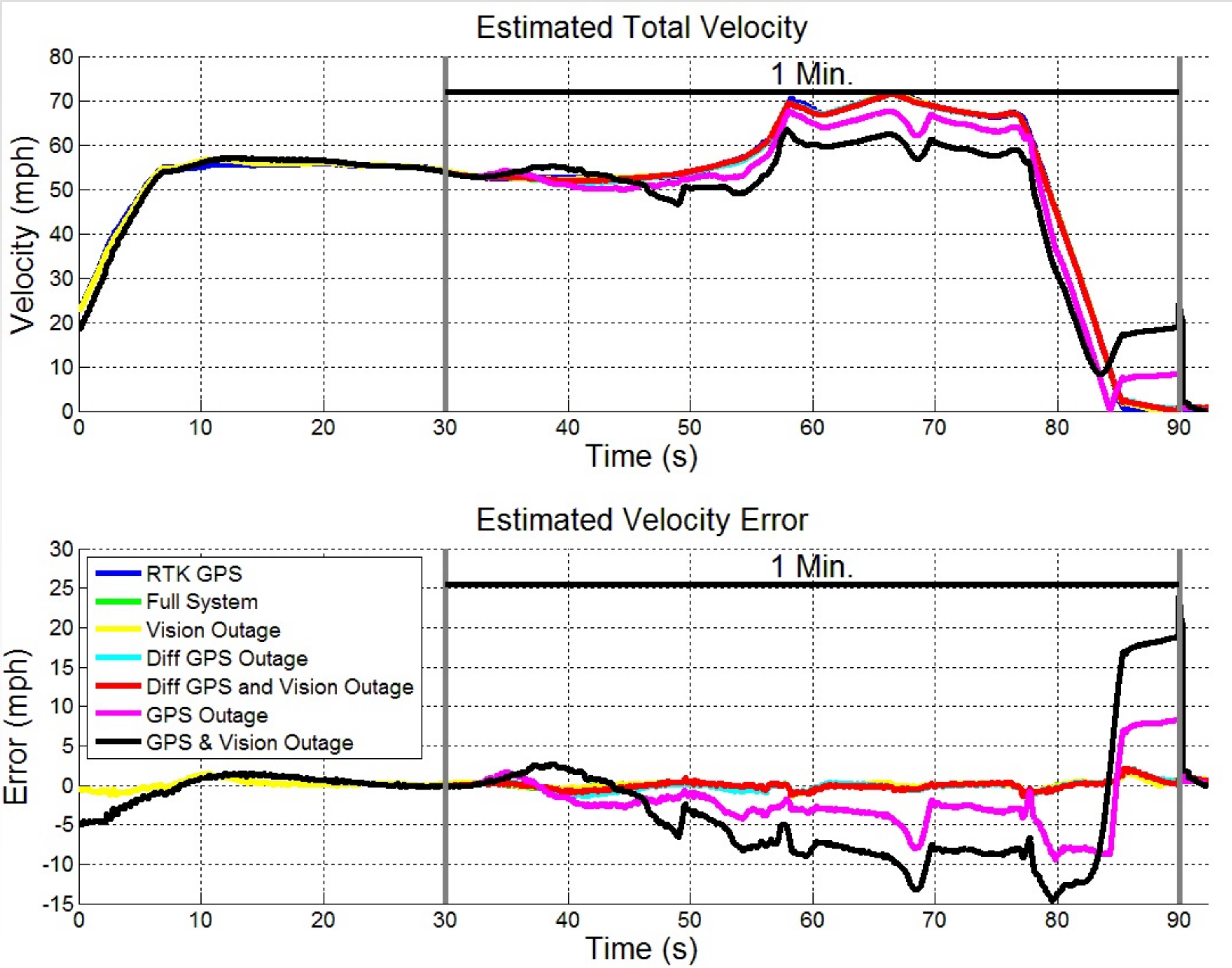
Results



Estimated Position
Filtered Position
Standalone GPS
Lane Center
Lane Lines
^ North
< South
-200
-300
-400
-800
-600
-400
< West East >
-105
-110
-115
-120
-780
-770
-760
-370
-380
-390
-400
-410
-420
-1080
-1060
-1040
-1020
-395
-400
-405
-410
-160
-150
-140


www.fraps.com
Failure Point
Google
Imagery Date: Jun 15, 2006

Results



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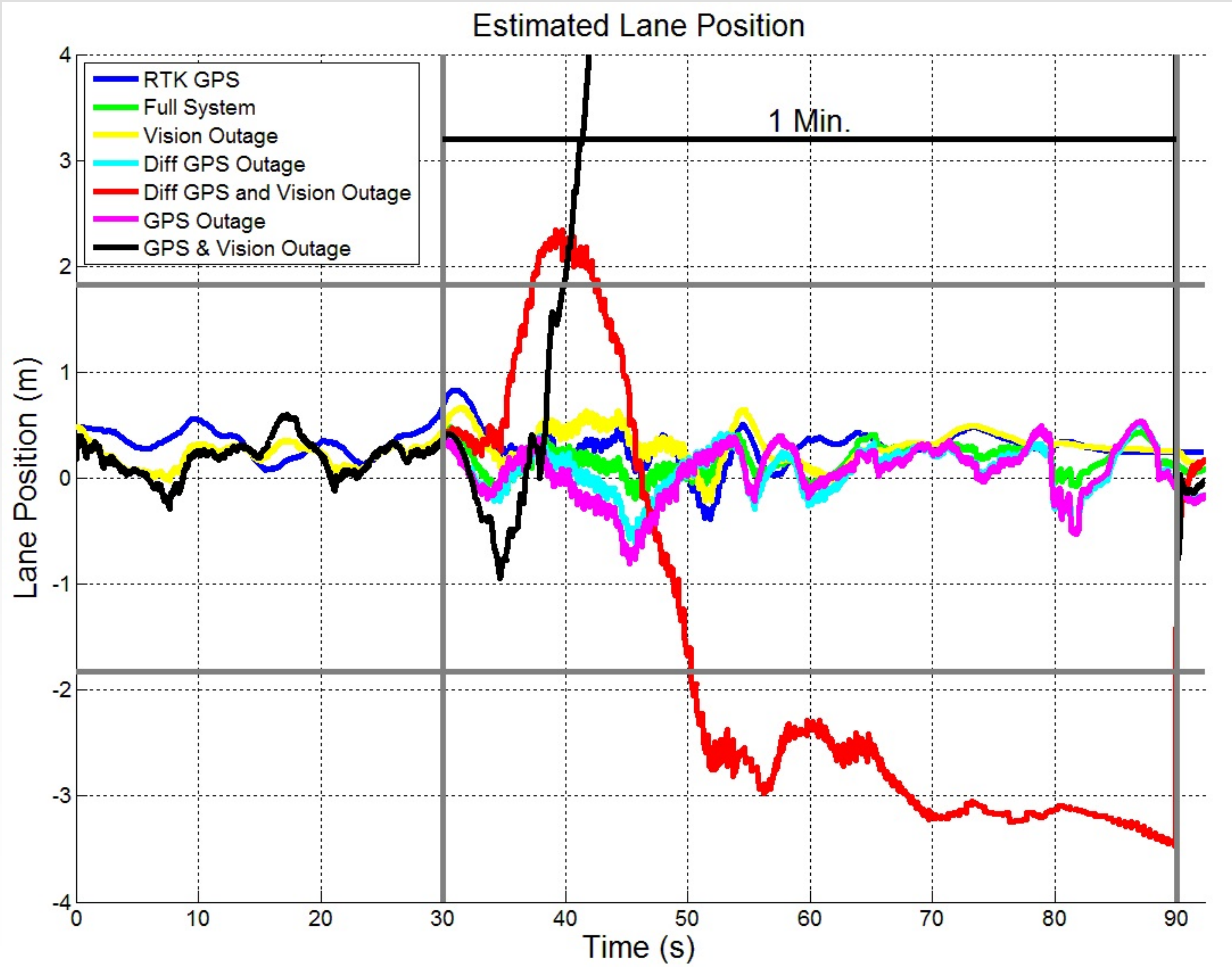
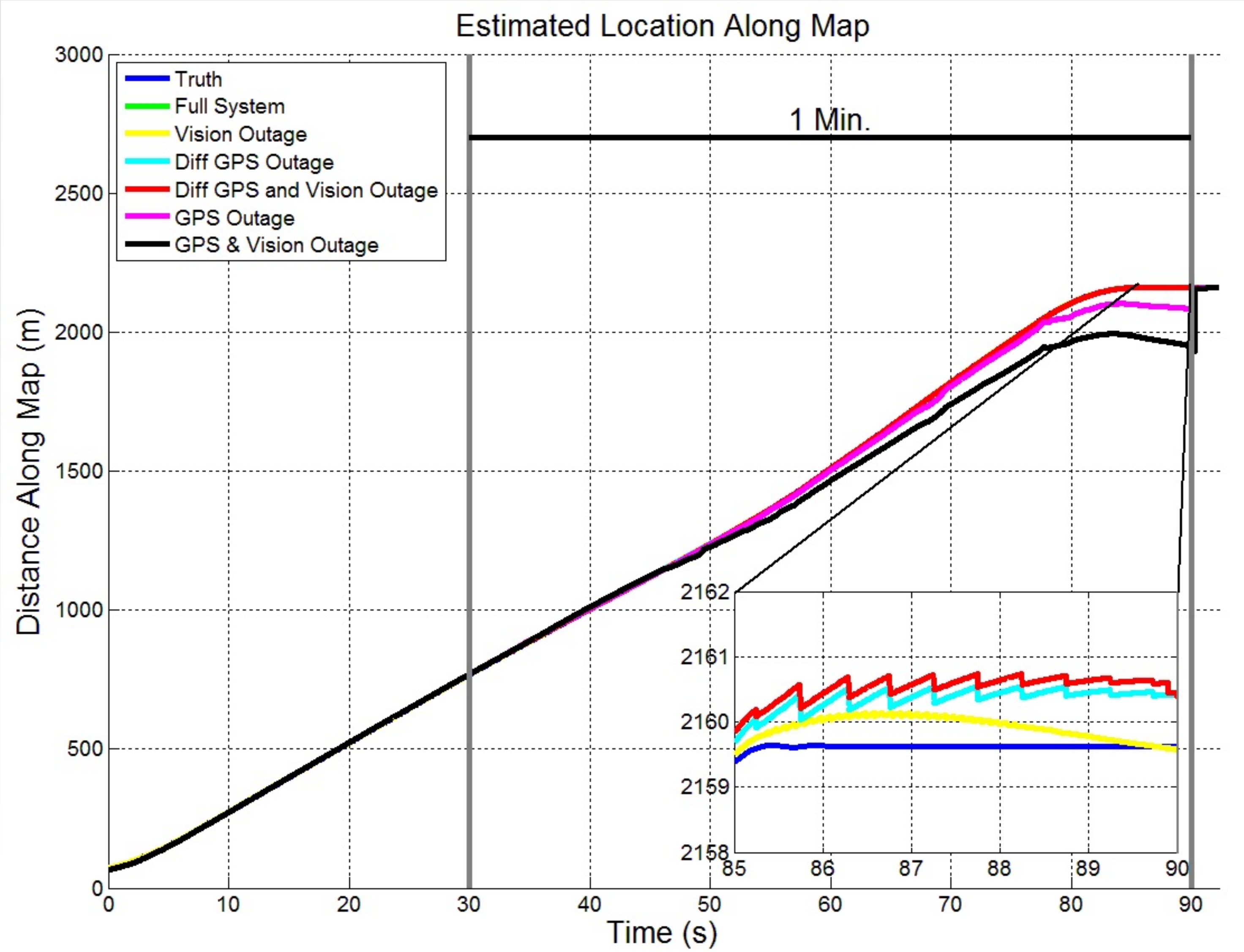
Results



Estimated Lane Position
RTK GPS
Full System
Vision Outage
Diff GPS Outage
Diff GPS and Vision Outage
GPS Outage
GPS & Vision Outage
1 Min.
Lane Position (m)
Time (s)
4
3
2
1
0
-1
-2
-3
-4
0
10
20
30
40
50
60
70
80
90

Results



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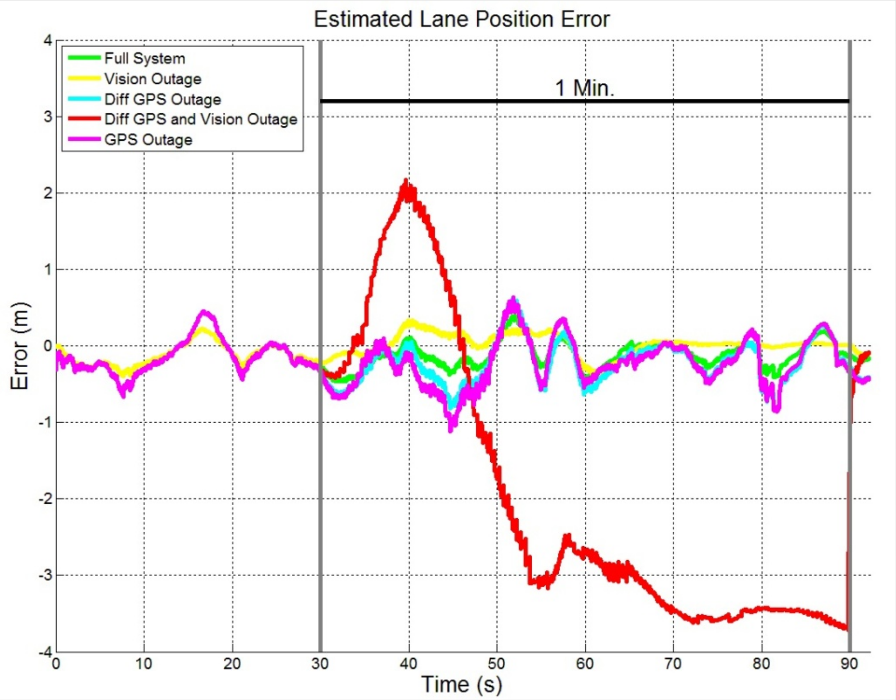
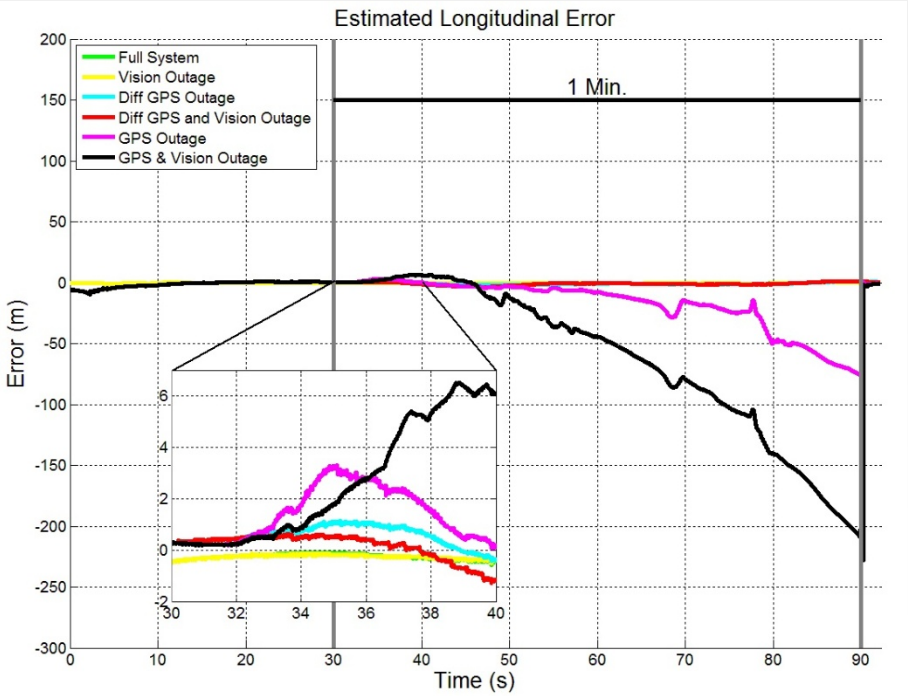
Results

- Availability of differential GPS or vision measurements will result in lane level accuracy.
  - Standalone GPS can not achieve lane level position without the aid of vision
- Longitudinal position remains accurate as long as GPS is available.
  - Vision can be used to maintain lane position with no GPS, however, this will result in longitudinal position drift





Observabilty Analysis

- 11 States
- These equation assume a steady state attitude
- G=gravity vector expressed in navigation coordinate frame
- u=IMU input
  - u_1-u_3=accelerometer inputs

states

$$\mathrm{X} = \begin{bmatrix} x \\ y \\ z \\ \dot{x} \\ \dot{y} \\ \dot{z} \\ b_{ax} \\ b_{ay} \\ b_{az} \\ ct_u \\ c\dot{t}_u \end{bmatrix} = \begin{bmatrix} X_1 \\ X_2 \\ X_3 \\ X_4 \\ X_5 \\ X_6 \\ X_7 \\ X_8 \\ X_9 \\ X_{10} \\ X_{11} \end{bmatrix}$$

EOM

$$\dot{\mathrm{X}}_{11\times 1} = \begin{bmatrix} X_{4:6} \\ C_{\mathrm{Body}}^{\mathrm{Nav}}(u_{1:3} - X_{7:9}) - G - \Omega \\ 0_{1\times 3} \\ X_{11} \\ 0 \end{bmatrix}$$

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Closely Coupled (4 Observations)

- rank(OBS)=11 if the unit vector to each SV is independent
- Requires at least 4 observations to be fully observable.

$$C=\begin{bmatrix} a_1 & b_1 & c_1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & a_1 & b_1 & c_1 & 0 & 0 & 0 & 0 & 1 \\ a_2 & b_2 & c_2 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & a_2 & b_2 & c_2 & 0 & 0 & 0 & 0 & 1 \\ a_3 & b_3 & c_3 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & a_3 & b_3 & c_3 & 0 & 0 & 0 & 0 & 1 \\ a_4 & b_4 & c_4 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & a_4 & b_4 & c_4 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

unit vector to sv1=$[a_1\ b_1\ c_1]$
unit vector to sv2=$[a_2\ b_2\ c_2]$
unit vector to sv3=$[a_3\ b_3\ c_3]$
unit vector to sv4=$[a_4\ b_4\ c_4]$

$$A=\begin{bmatrix} O_{3\times3} & I_{3\times3} & O_{3\times3} & O_{3\times1} & O_{3\times1} \\ O_{3\times3} & O_{3\times3} & -C_{BODY}^{NAV} & O_{3\times1} & O_{3\times1} \\ O_{3\times3} & O_{3\times3} & O_{3\times3} & O_{3\times1} & O_{3\times1} \\ O_{1\times3} & O_{1\times3} & O_{1\times3} & 1 & 0 \\ O_{1\times3} & O_{1\times3} & O_{1\times3} & 0 & 0 \end{bmatrix}$$

$$OBS=\begin{bmatrix} C \\ CA \\ CA^2 \\ .... \\ CA^{13} \end{bmatrix}$$

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H Tightly Coupled (2 Observations)

$$H = \begin{bmatrix} a_1 & b_1 & c_1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & a_1 & b_1 & c_1 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ a_2 & b_2 & c_2 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & -1 & 0 \\ 0 & 0 & 0 & a_2 & b_2 & c_2 & 0 & 0 & 0 & 0 & 0 & 0 & -1 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \end{bmatrix} \longrightarrow C = \begin{bmatrix} a_1 & b_1 & c_1 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & a_1 & b_1 & c_1 & 0 & 0 & 0 & 0 & 1 \\ a_2 & b_2 & c_2 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & a_2 & b_2 & c_2 & 0 & 0 & 0 & 0 & 1 \\ a_3 & b_3 & c_3 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ a_4 & b_4 & c_4 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

rank(obs)=8

$$OBS = \begin{bmatrix} C \\ CA \\ CA^2 \\ .... \\ CA^{13} \end{bmatrix}$$

rank(obs)=11

Observability Analysis (2 Observations)

	Elevation	Azimuth
SV1	60	90
SV2	30	-90

$$H = \begin{bmatrix} 0 & .5 & -.866 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & .5 & -.866 & 0 & 0 & 0 & 0 & 1 \\ 0 & -.866 & -.5 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & -.866 & -.5 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

- No x axis position or x axis velocity information is provided by the GPS observations. This causes a loss of observability.

$$OBS = \begin{bmatrix} C \\ CA \\ CA^2 \\ .... \\ CA^{13} \end{bmatrix}$$

rank(obs)=10

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Observability Analysis (2 Observations)

	Elevation	Azimuth
SV1	45	0
SV2	45	180

$$H = \begin{bmatrix} .707 & 0 & -.707 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & .707 & 0 & -.707 & 0 & 0 & 0 & 0 & 1 \\ -.707 & 0 & -.707 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & -.707 & 0 & -.707 & 0 & 0 & 0 & 0 & 1 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

- No y axis position or y axis velocity information is provided by the GPS observations: however, the system is still observable because the vision measurements provide information in the y axis.

$$OBS = \begin{bmatrix} C \\ CA \\ CA^2 \\ .... \\ CA^{13} \end{bmatrix}$$

rank(obs)=11

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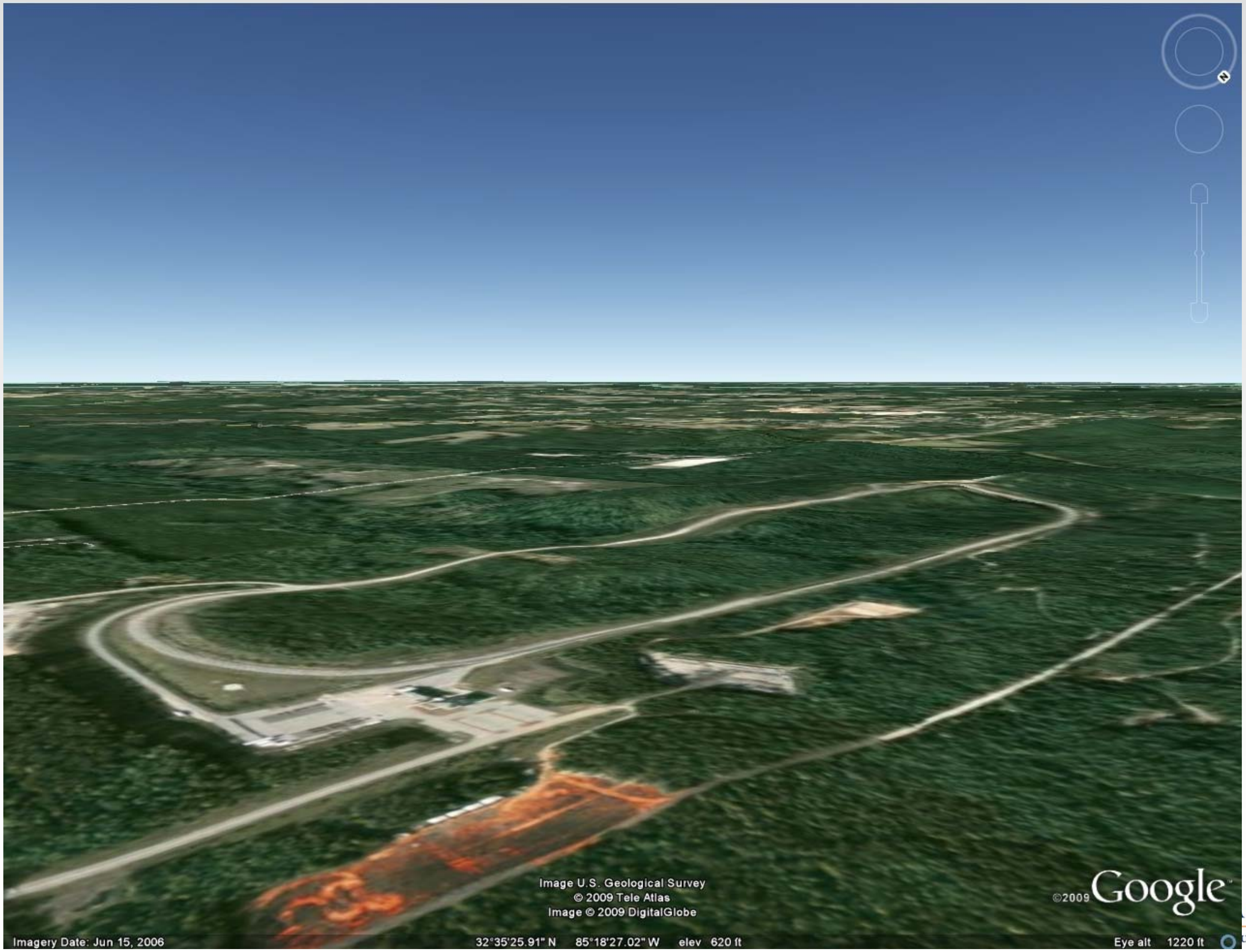
NCAT Test Track



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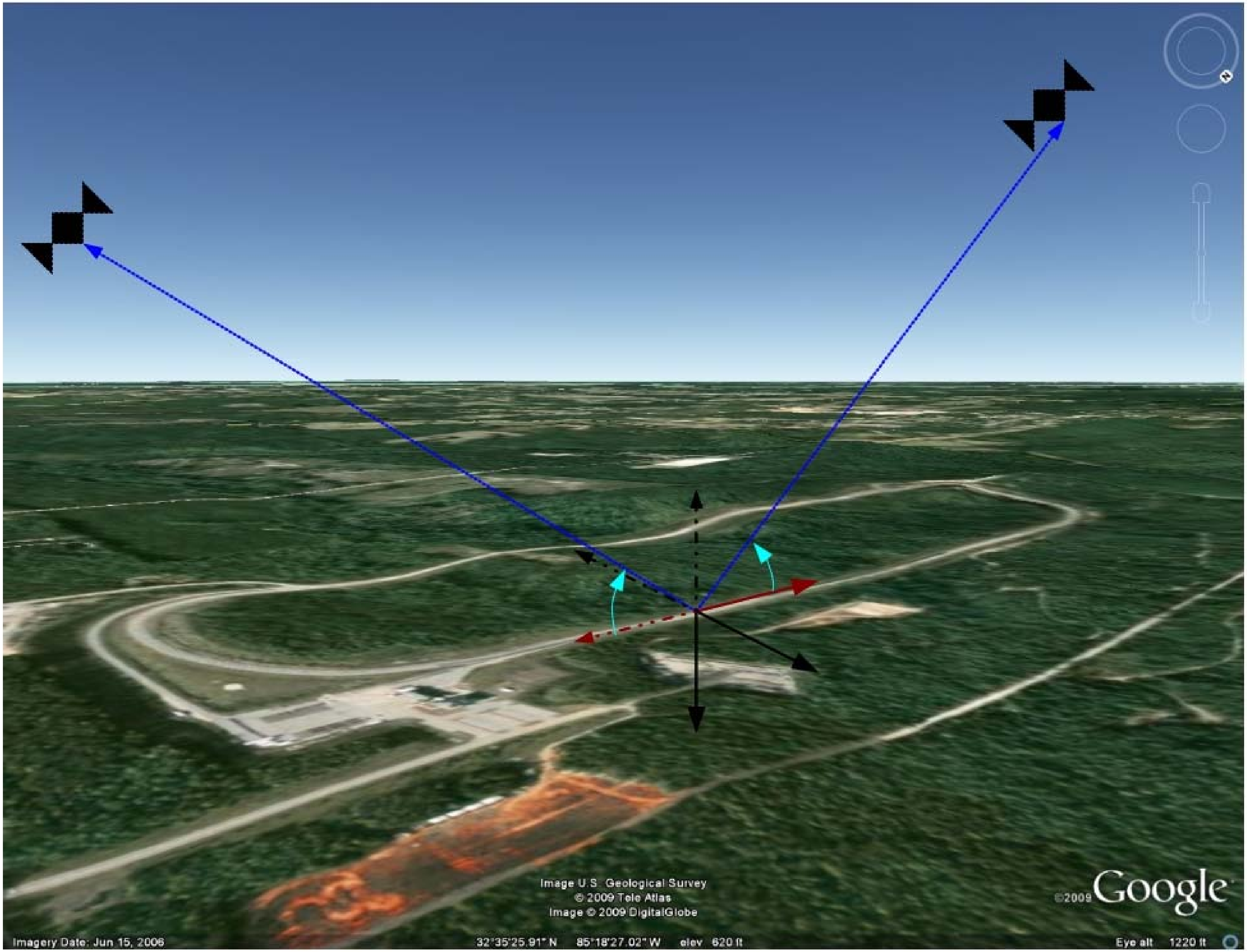
Image U.S. Geological Survey
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Image © 2009 DigitalGlobe
©2009 Google
Imagery Date: Jun 15, 2006
32°35'25.91" N 85°18'27.02" W elev 620 ft
Eye alt 1220 ft

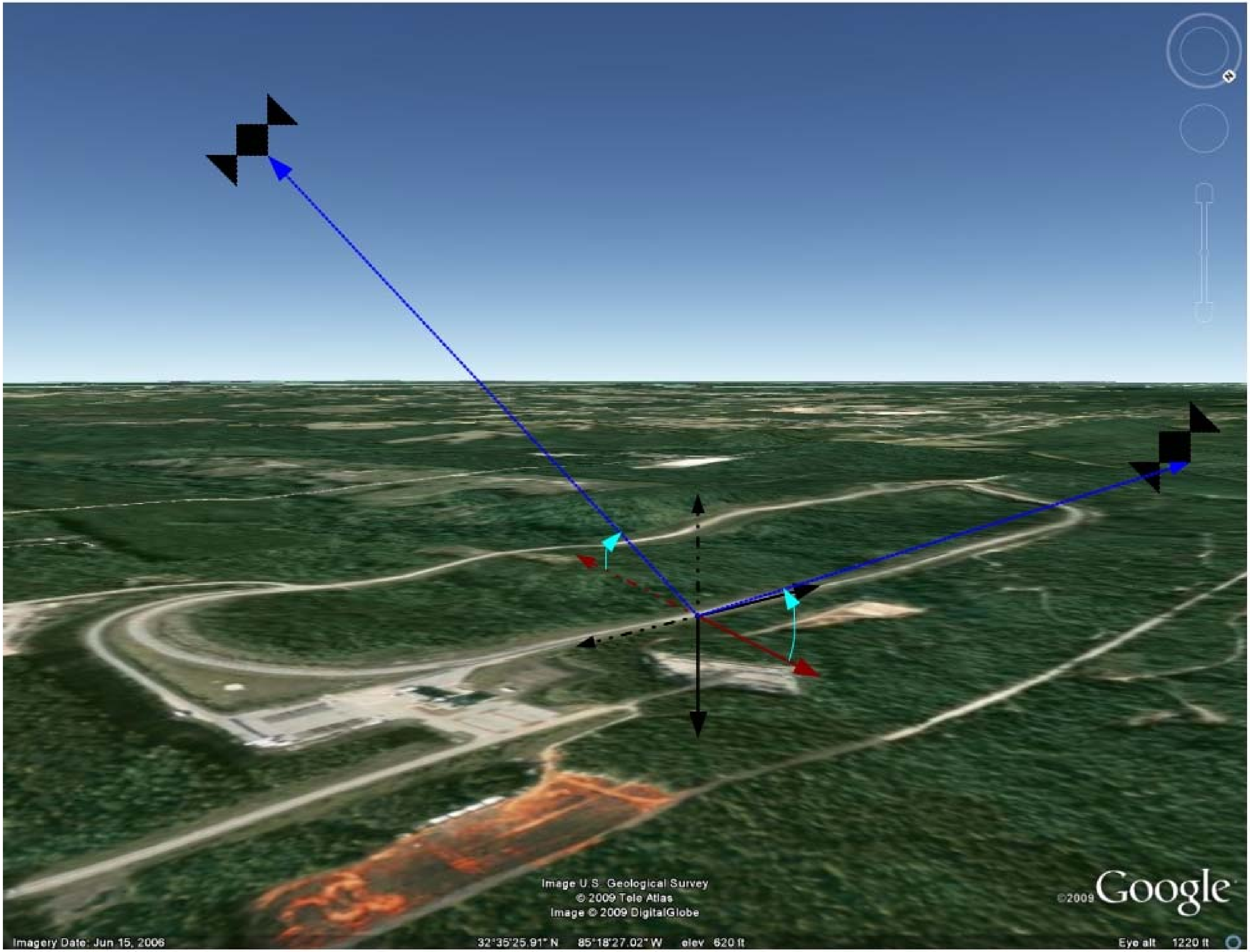

Image U.S. Geological Survey
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Imagery Date: Jun 15, 2006
32°35'25.91" N 85°18'27.02" W elev 620 ft
Eye alt 1220 ft

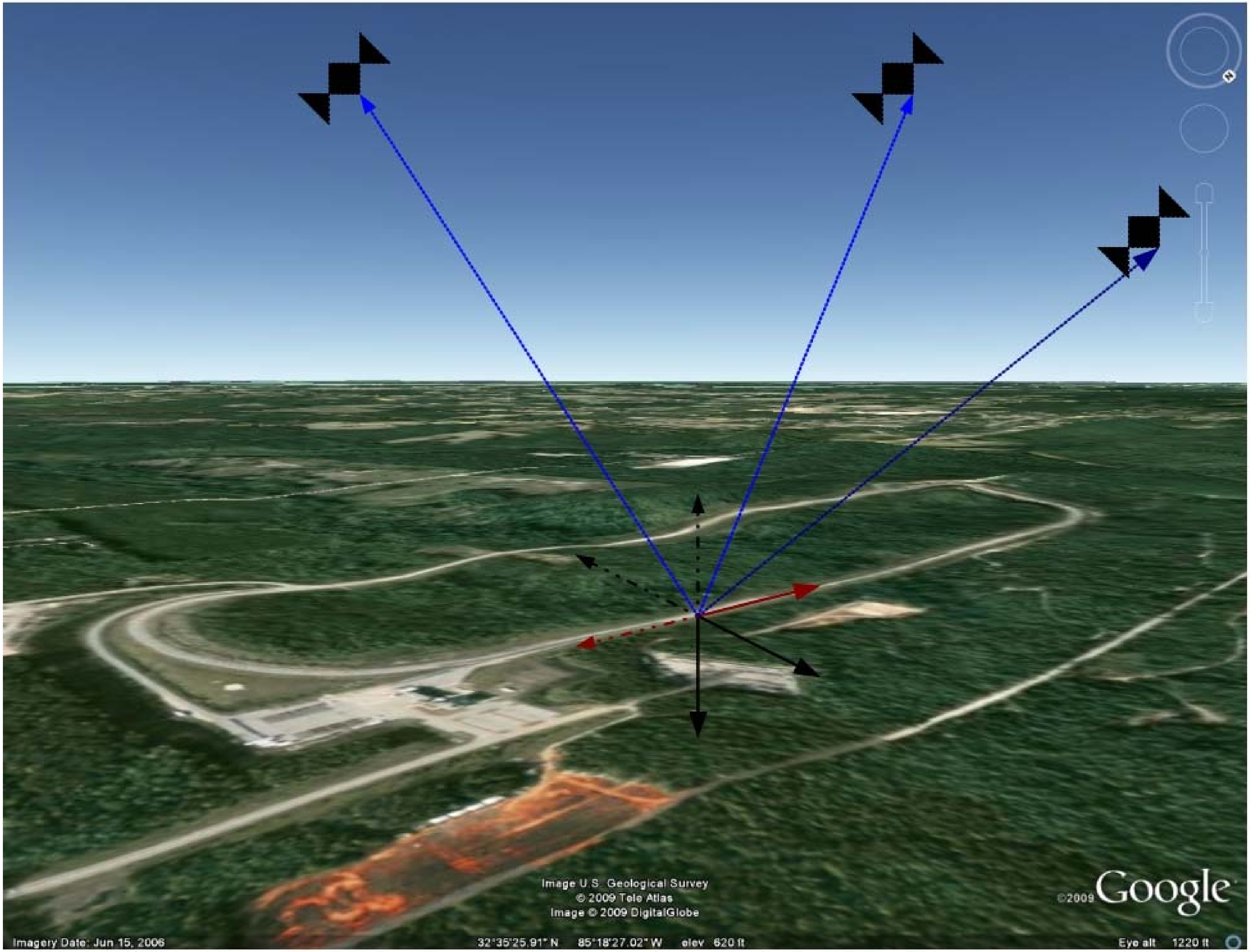

Image U.S. Geological Survey
© 2009 Tele Atlas
Image © 2009 DigitalGlobe
©2009 Google
Imagery Date: Jun 15, 2006
32°35'25.91" N 85°18'27.02" W elev 620 ft
Eye alt 1220 ft

Results

	Elevation	Azimuth
SV5	19	63
SV9	16	151
SV15	80	100
SV18	38	-80
SV21	52	-39
SV26	44	47
SV27	25	129
SV29	49	148

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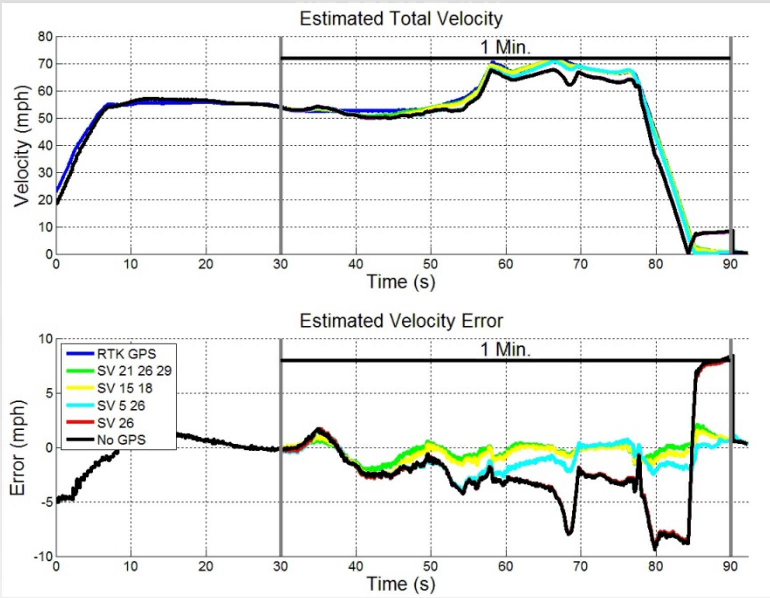
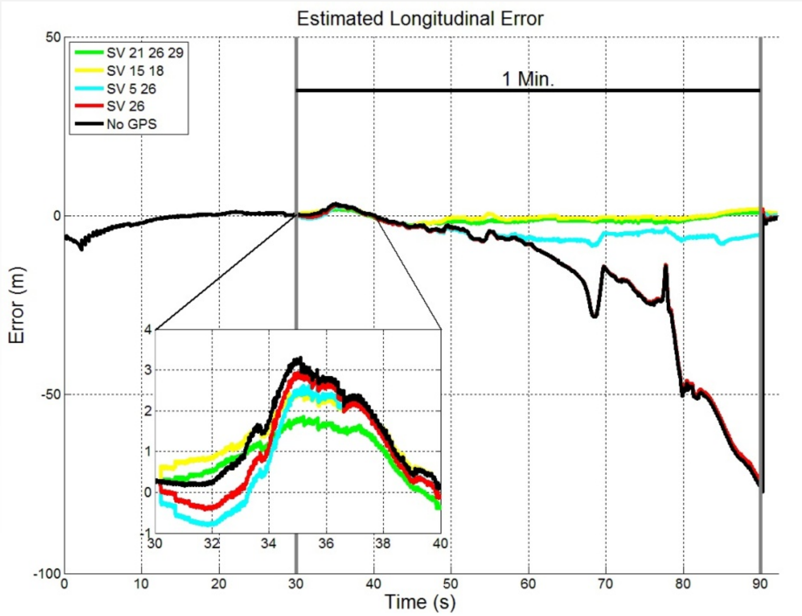
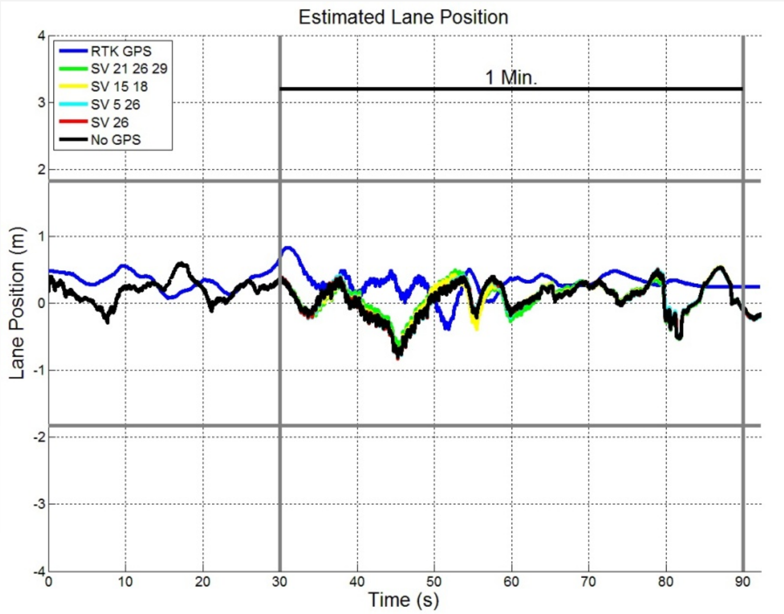
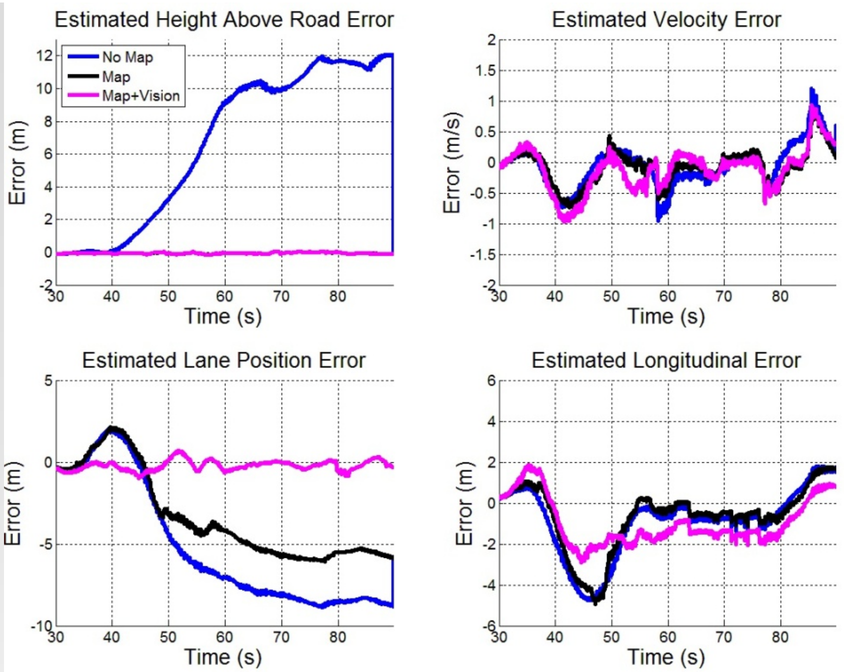
Results

- Velocity error directly corresponds to number of observations available
- Using vision during satellite outages results in better overall velocity estimation
- There is no benefit when using only 1 GPS observation

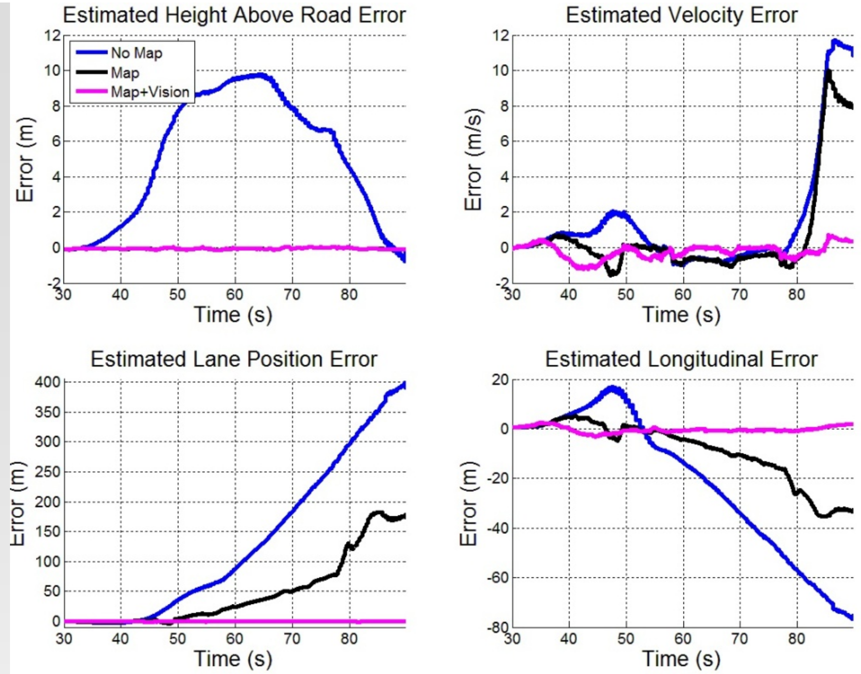




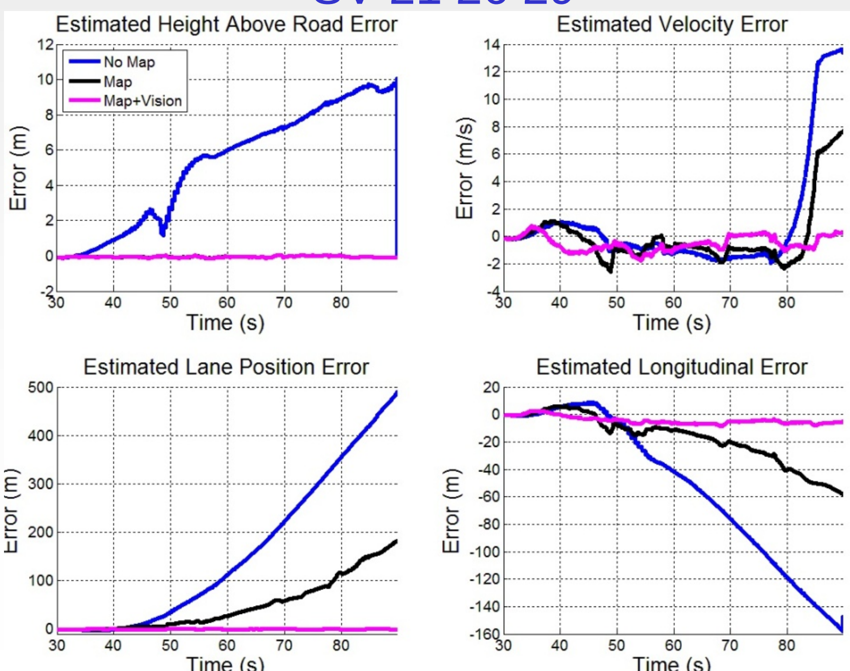




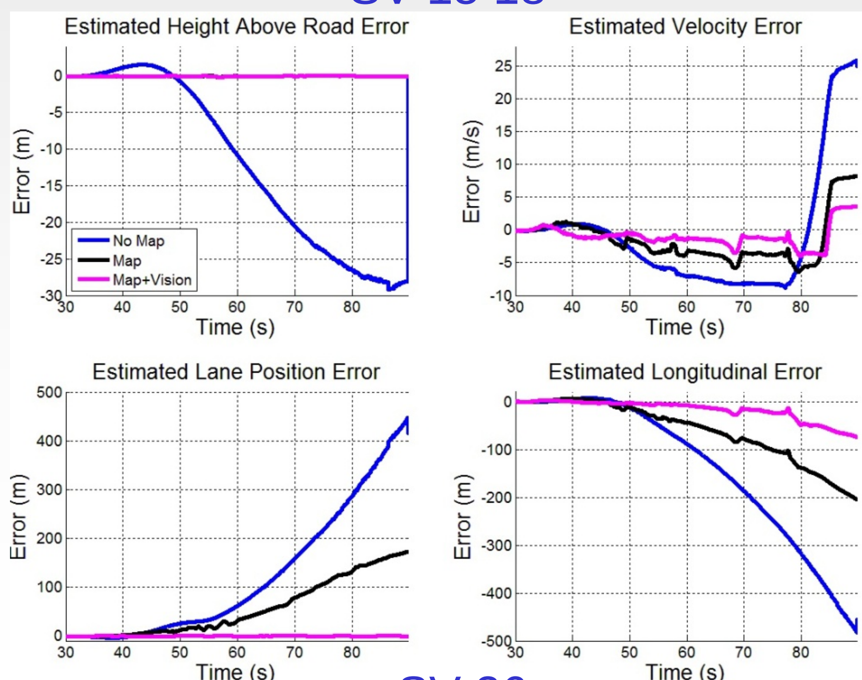
SV 21 26 29



SV 15 18



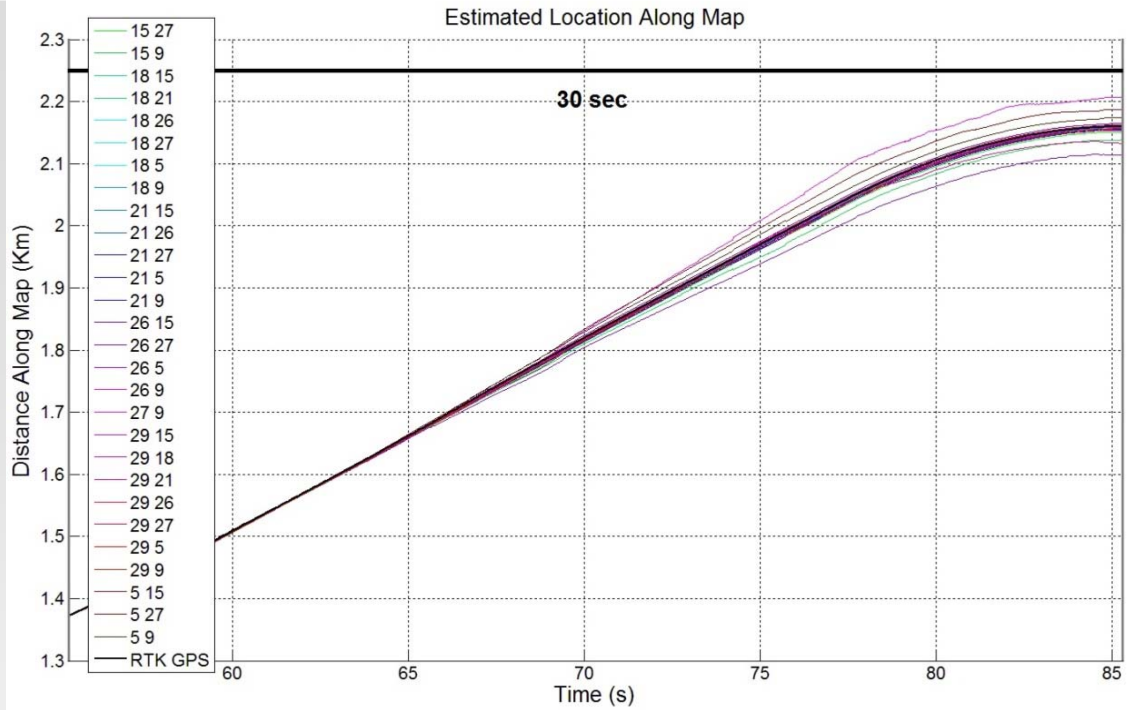
SV 5 26

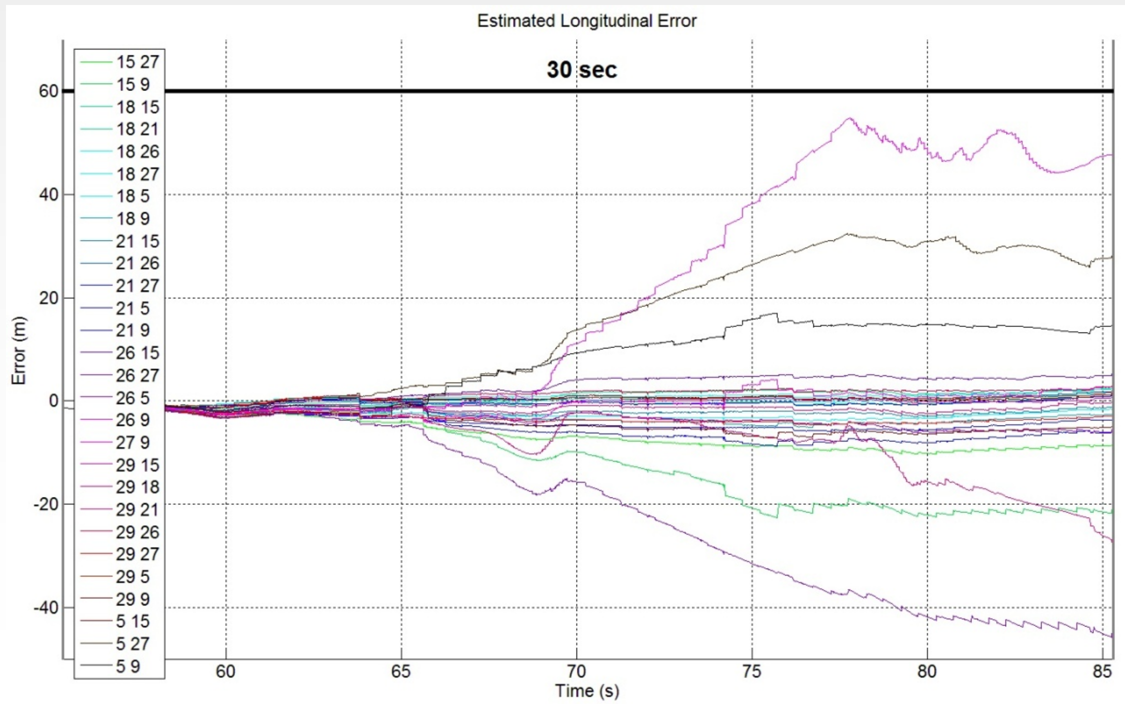


SV 26

Results

	C2N
SV5	48
SV9	48
SV15	54
SV18	53
SV21	52
SV26	48
SV27	42
SV29	51





Conclusions

- It is possible to use measurements in a coordinate frame that is not aligned with the navigation coordinate frame.
- This technique can be applied to any situation where the measurement coordinate frame and navigation coordinate frame do not align.
- Using an accurate map along with vision based lane position measurements will improve global accuracy in 2 dimensions.
- It is possible to have a fully observable navigation filter only using 2 GPS satellites as long as supplemental measurements are provided. Using only 2 GPS satellites will result in more estimate error than using a full GPS satellite constellation.
- Effects of satellite geometry will increase as the number of GPS observations used decreases.

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Future Work

- Use multiple waypoint maps to create a filter that can track lane changes and track the current lane the vehicle resides
- Use DSRC ranging, visual odometry, and road signature maps to further improve robustness
- Develop maps that incorporate road bank
- Develop maps that are equation based instead of way-point based.
- Use of SLAM or other techniques simultaneous positioning and mapping.

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