Improving the Detection Capability of Vertical and Horizontal Failures in Terrain Database Integrity Monitors

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Introduction

- A Flight Safety Foundation Study revealed that 41% of all aircraft accidents involved Controlled Flight into Terrain (CFIT)
- CFIT means the aircraft runs into terrain (mountains, or land while flying low) even though the aircraft is under full control of the pilot
- Principal cause of CFIT is loss of spatial orientation during zero visibility conditions due to bad weather like rain, fog, snow or darkness

Remedial Measures

Government Programs

- NASA's Aviation Safety Program
  - » **Synthetic Vision Systems (SVS) Project**
- FAA's Safeflight21 Program
- NIMA's Ron Brown Airfield Initiative

What Are Synthetic Vision Systems ?

- Advanced display technology containing information about aircraft state, guidance, navigation, surrounding terrain and traffic
- A computer generated (*synthetic*) image of the outside world as viewed "from the cockpit"
- Provides either a Heads-Up Display (HUD) or a Heads-Down Display (HDD)
- Clear view in all weather conditions at all times

Source of Synthetic Vision Displays

- Digitally stored terrain heights known as Digital Elevation Models (DEMs) or Digital Terrain Elevation Databases (DTEDs)
- Similar to having a digital lookup table containing terrain heights
- Eg: DTED level 0,1,2, Jeppesen

Why Terrain Database Integrity Monitoring ?

Terrain Databases may have systematic faults due to:

- Different sensor technologies used to generate the terrain databases
- Manual post – processing of collected data
- Flat earth approximation over relatively large areas

Use of Synthetic Vision Displays for functions other than their intended applications

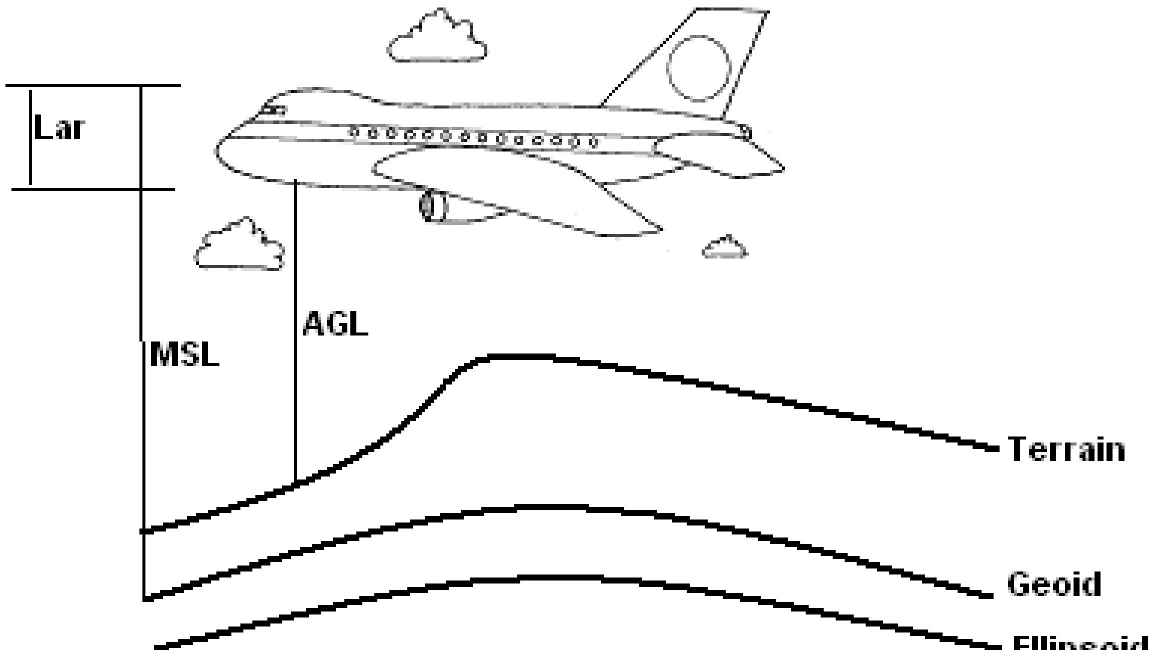
Errors Present in Terrain Databases

Errors in the form of:

- Bias – due to coordinate transformation mismatch
  - » Vertical domain
  - » Horizontal domain
- Ramps
  - » Vertical domain
  - » Horizontal domain
- Random Errors
  - » Distributed errors in Vertical Domain
  - » Circularly distributed errors in the Horizontal Domain

Vertical Direction Integrity Monitor

Comparison of the DEM terrain profile with and independent terrain profile synthesized from a downward looking sensor such as a Radar Altimeter (RA) and GPS WAAS measurements*



Synthesized Height = MSL – AGL – Lar

DTED Height = elevation with respect to MSL

* Dr. Robert Gray's original Integrity Monitoring Concept

Comparison Metrics

The metrics used to express agreement between the two terrain profiles are:

- Absolute Disparity: $p(t_i) = h_{synt}(t_i) - h_{DTED}(t_i)$
  - » Sensitive to bias errors

Mean Squared Difference (MSD) = $\frac{1}{N}\sum_{i=1}^{N} p^2(t_i)$

- Successive Disparity: $s(t_i) = p(t_i) - p(t_{i-1})$
  - » Sensitive to ramp errors

Mean Absolute Difference (MAD) = $\frac{1}{N-1}\sum_{i=2}^{N} s^2(t_i)$

- Cross Correlation (XCORR)

These metrics are random variables and would require test statistics for their characterization

Formulation of Hypotheses

- Null or Fault – Free Hypothesis:
  - » Nominal error performance: just normal random errors

$$\mathrm{H}_0 : p_0 \sim N\left(0, \sigma_p^2\right)$$

Normally distributed errors with zero mean (no bias) and known convolved variance of errors σ_p^2

- Alternative or Faulted Hypothesis:
  - » Off-nominal behavior: failure, which means the presence of bias and ramp errors

$$\mathrm{H}_1 : p_1 \sim N\left(\mu_B, \sigma_p^2\right)$$

Normally distributed errors with mean μ_B (bias) and variance σ_p^2

So, Why Do We Need a Statistical Framework?

The distribution of the metrics used to perform hypothesis testing which is nominally due to the inherent presence of:

- Measurement noise on sensors used for comparison (RA, GPS positions)
- Vertical and Horizontal Error probability specification of the DEM
- Random errors on the DEM
- Ground Cover (Vegetation)

The 'T' Statistic for Hypothesis Testing

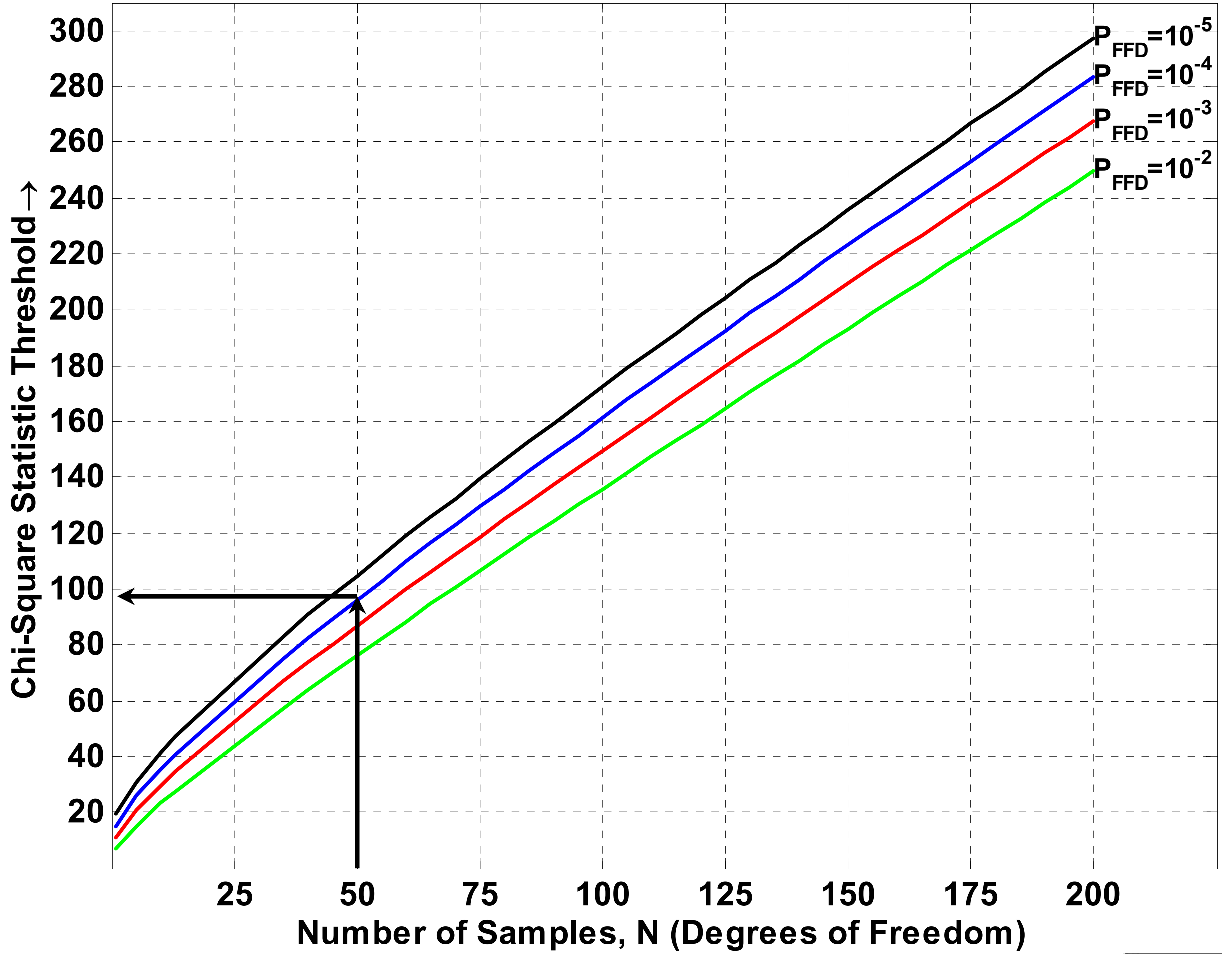
If the MSE is scaled by the variance of the noise on the absolute disparities under nominal conditions, it gives rise to a test statistic, T, which is a measure of consistency between the two terrain profiles.

$$T = \frac{1}{\sigma_p^2} \sum_{i=1}^{N} p^2(t_i)$$

This is a standard Chi – Squared statistic, but what should be its Threshold ?

How Do We Know the Threshold for T ?

The threshold value for T is determined by the probability of Fault – Free Detection, P_{FFD} and the number of degrees of freedom,N



Horizontal Integrity Monitor
Multiple Path DLIM

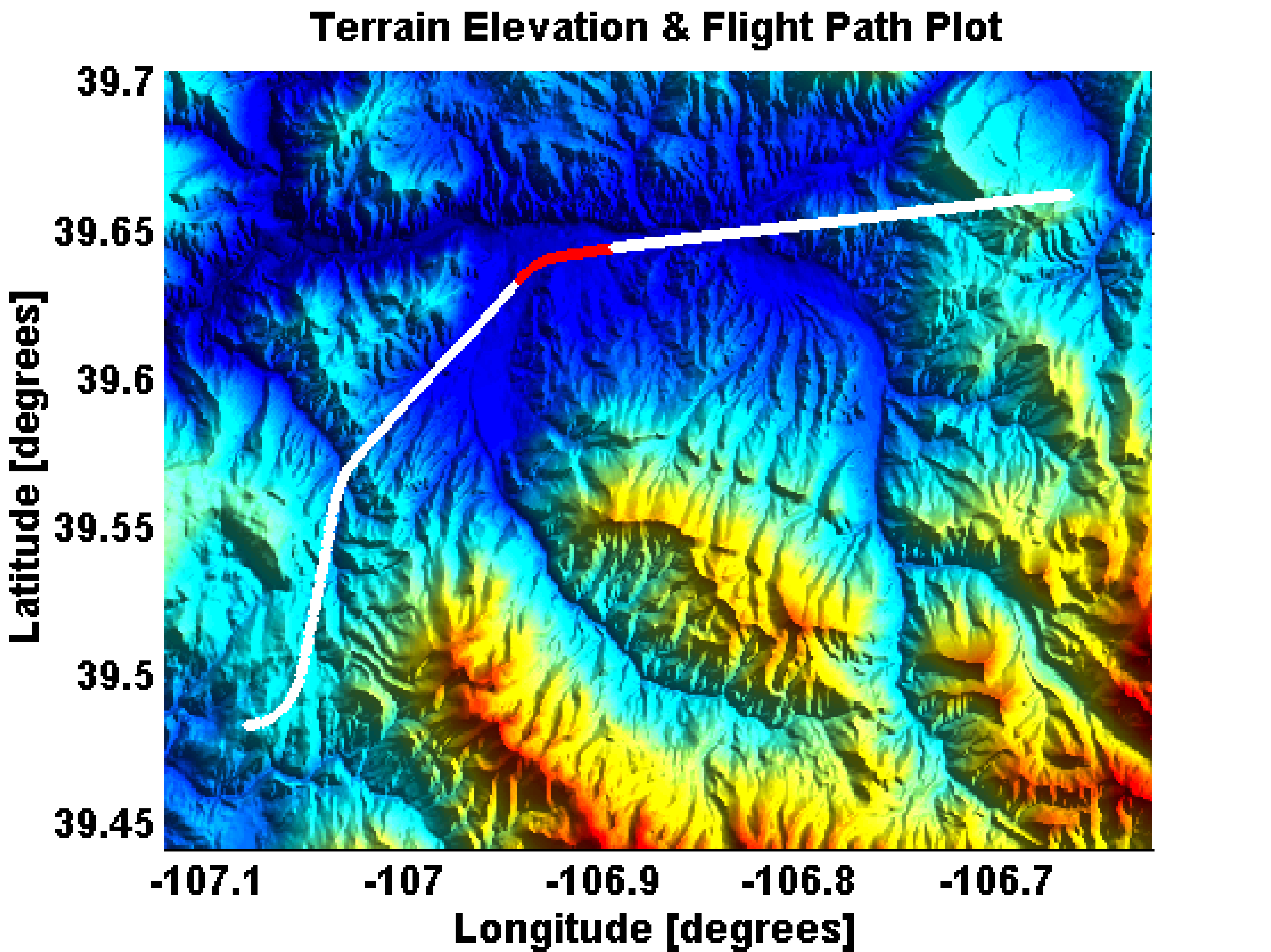
- Look for multiple flight paths parallel to the nominal over a search grid and compute the chi – squared test statistic as a measure of conformity between the two terrain profiles.

$$T(m,n)=\frac{1}{\sigma^2}\sum_{i=1}^{N}\left(h_{SYNT}(t_i)-h_{DTED}(x,y)\right)^2$$

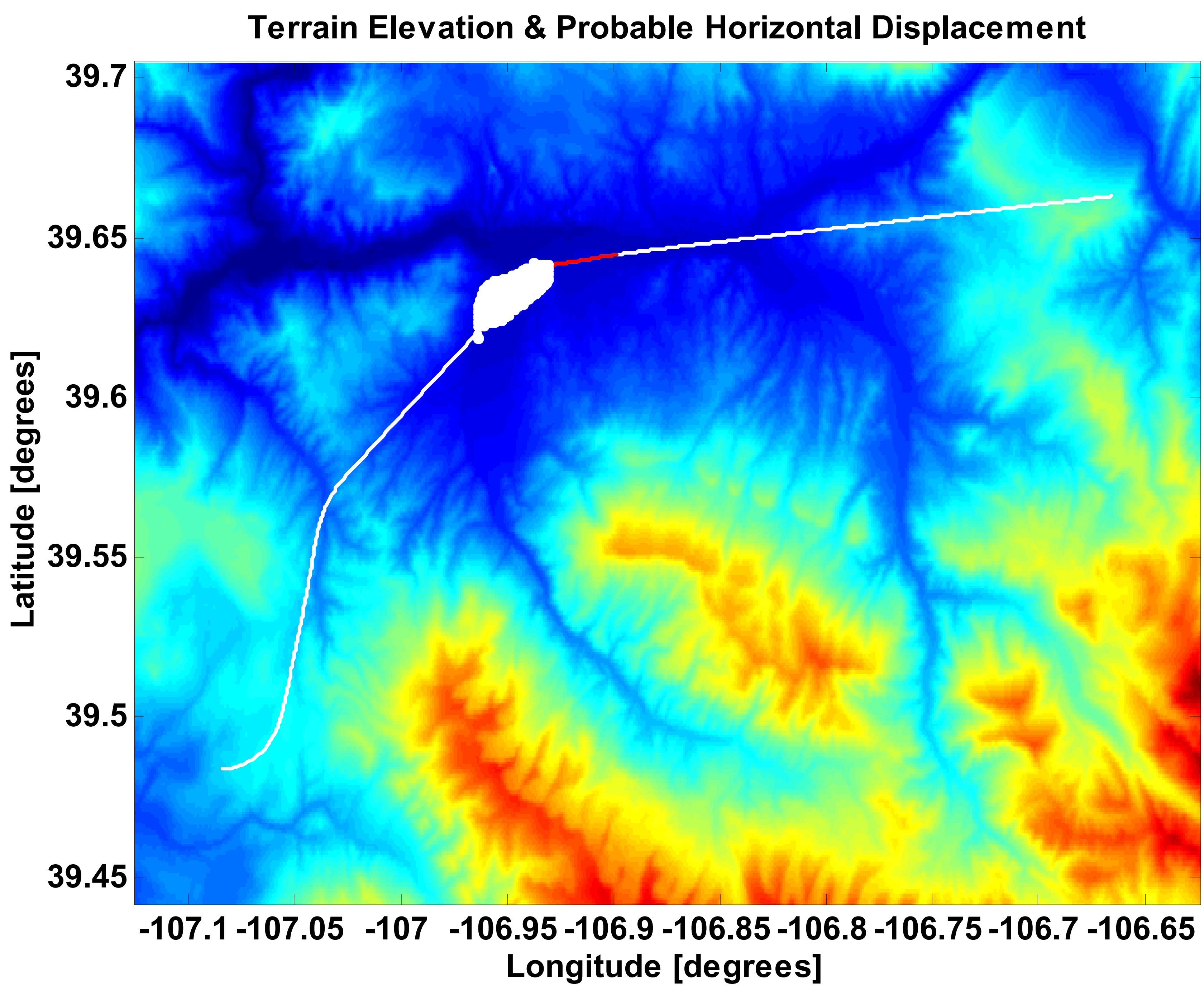
$$Where,\quad x=lat(t_i)+lat\_offset_m \quad for \quad m=-P \quad to \quad P$$

$$y=lon(t_i)+lon\_offset_n \quad for \quad n=-P \quad to \quad P$$

- Determine if one or more of these translated positions are the actual positions on the DTED corresponding to the DGPS position



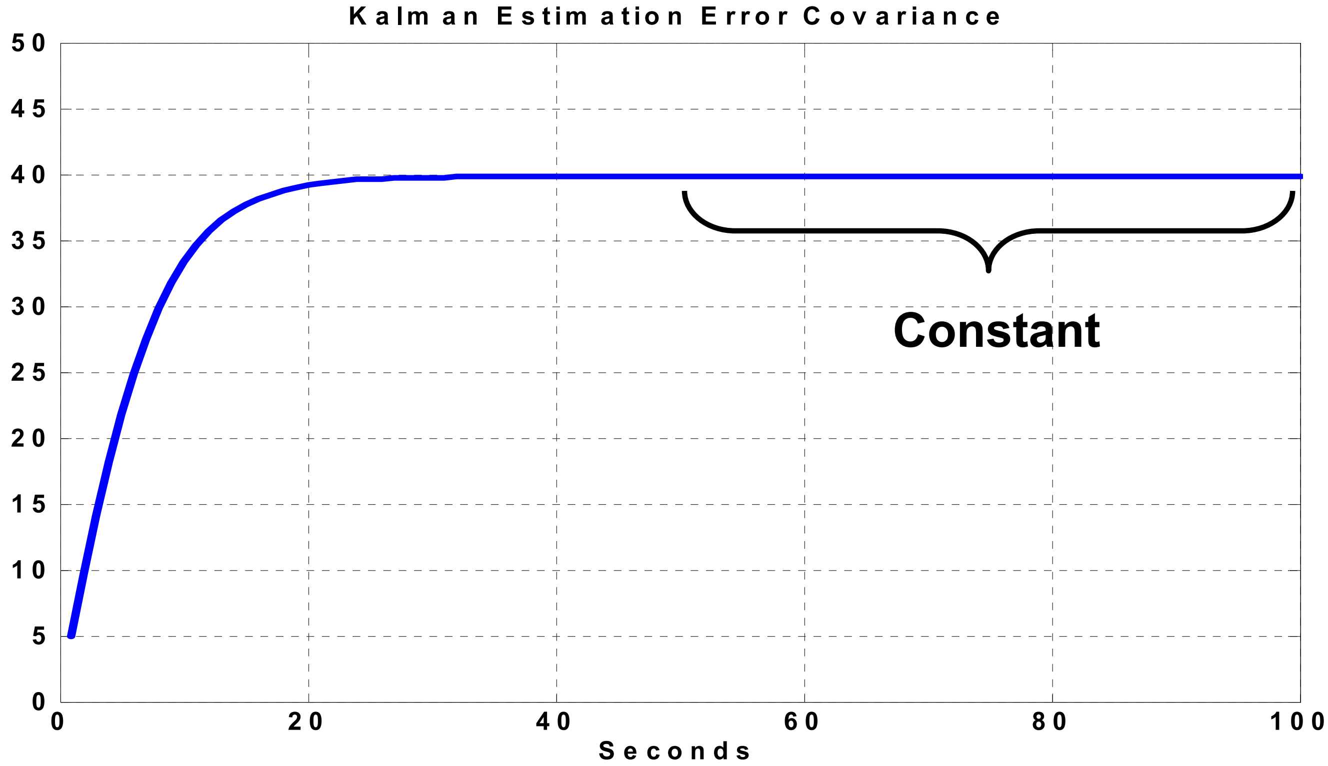
Terrain Elevation & Flight Path Plot
39.7
39.65
39.6
39.55
39.5
39.45
Latitude [degrees]
-107.1
-107
-106.9
-106.8
-106.7
Longitude [degrees]


Terrain Elevation & Probable Horizontal Displacement
39.7
39.65
39.6
39.55
39.5
39.45
Latitude [degrees]
-107.1
-107.05
-107
-106.95
-106.9
-106.85
-106.8
-106.75
-106.7
-106.65
Longitude [degrees]

Filtering of Absolute Disparities

Estimation of bias if it were to be present

- Ordinary Least Squares Filtering
- Kalman Filtering



Kalman Filter Equations

Enter prior estimate $\hat{x}_0$ **and its error covariance** P_0^-

Compute Kalman gain:

$$K_k = P_k^- H_k^T \left(H_k P_k^- H_k^T + R_k \right)^{-1}$$

$z_0, z_1, \ldots$

Update estimate with measurement :

$$\hat{x}_k = \hat{x}_k^- + K_k \left(z_k - H_k \hat{x}_k^- \right)$$

$$\hat{x}_0, \hat{x}_1, \ldots$$

Compute error covariance for updated estimate:

$$P_k = \left(I - K_k H_k \right) P_k^-$$

Project Ahead:

$$\hat{x}_{k+1}^- = \phi_k \hat{x}_k$$

$$P_{k+1}^- = \phi_k P_k \phi_k^T + Q_k$$

Where,

x_k is the process state vector at time t_k

ϕ_k is the state transition matrix

z_k is the measurement at time t_k

H_k is the domain transition matrix

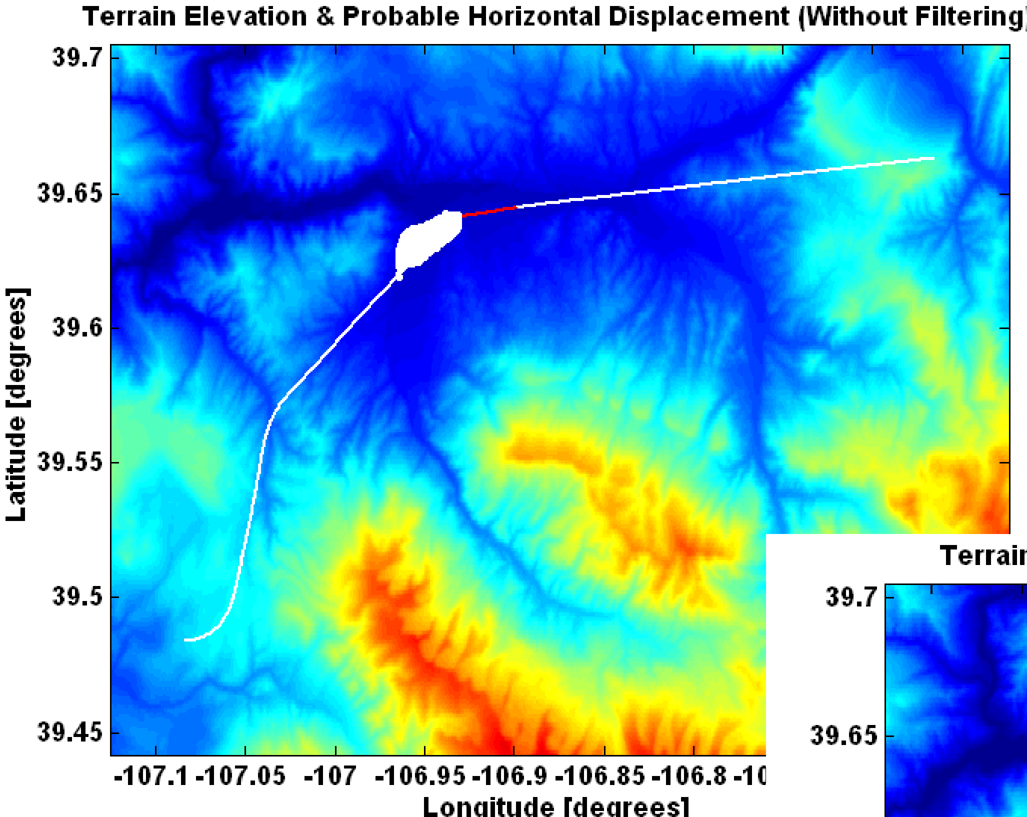
P_k is the estimation error covariance matrix

R_k is the measurement error covariance matrix

Q_k is the system noise covariance matrix

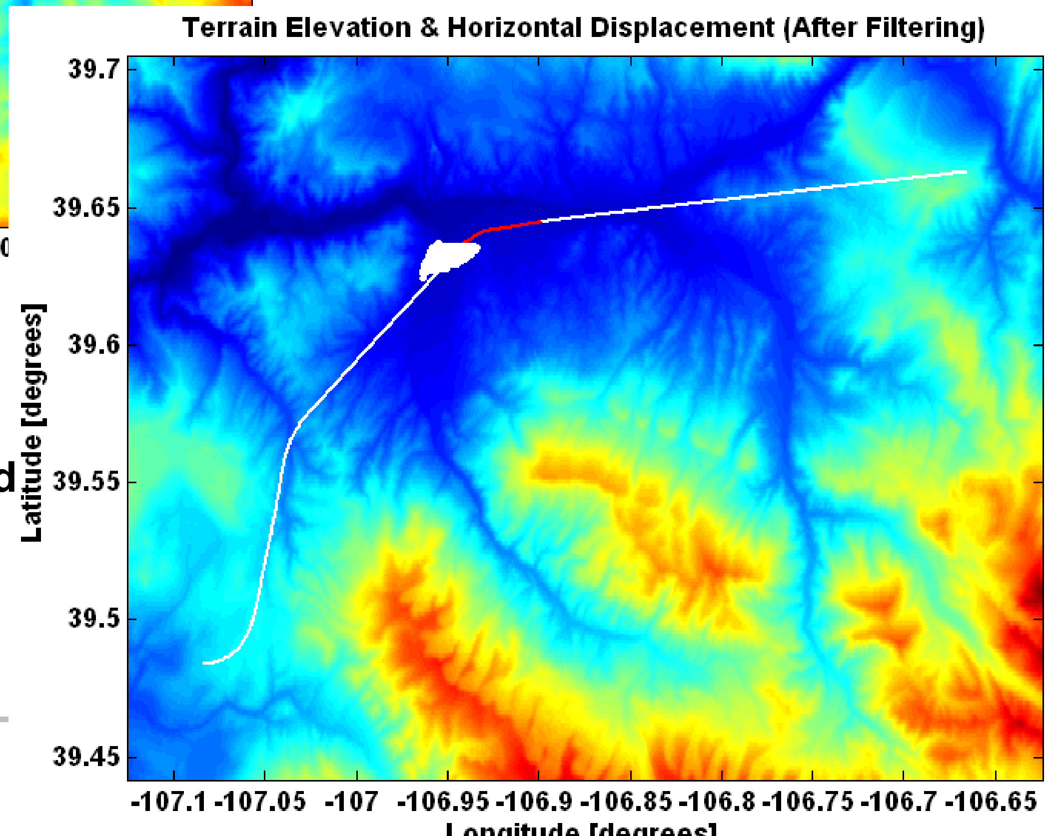
Kalman filtering could be used for both terrain database integrity monitoring and terrain navigation. An illustration of the former follows

Approach to R/W 25, EGE



Minimum T offset = 92.6 m South and 71.3 m West

Maximum Displacement = 2,124 m



Minimum T offset = 92.6 m South and 214 m West

Maximum Displacement = 1,641 m

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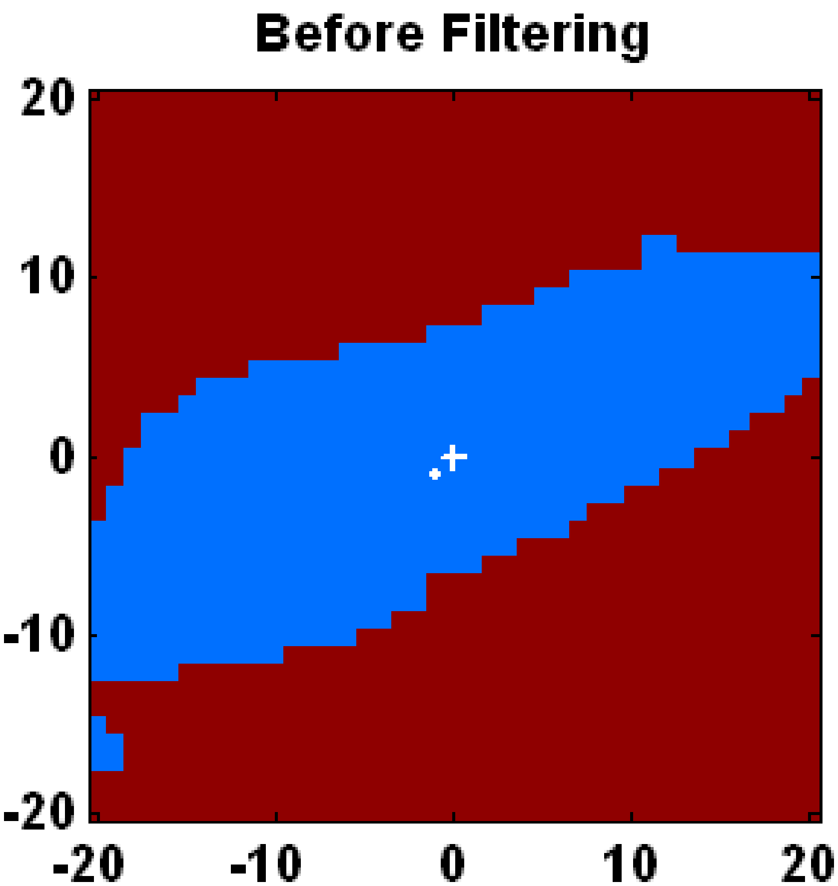
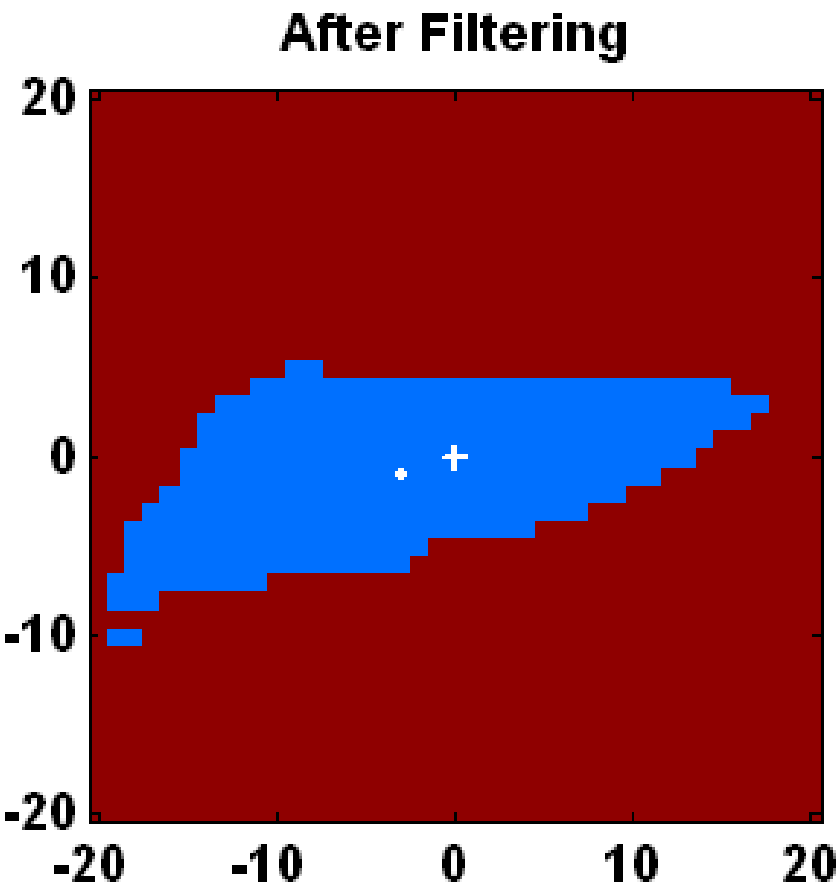
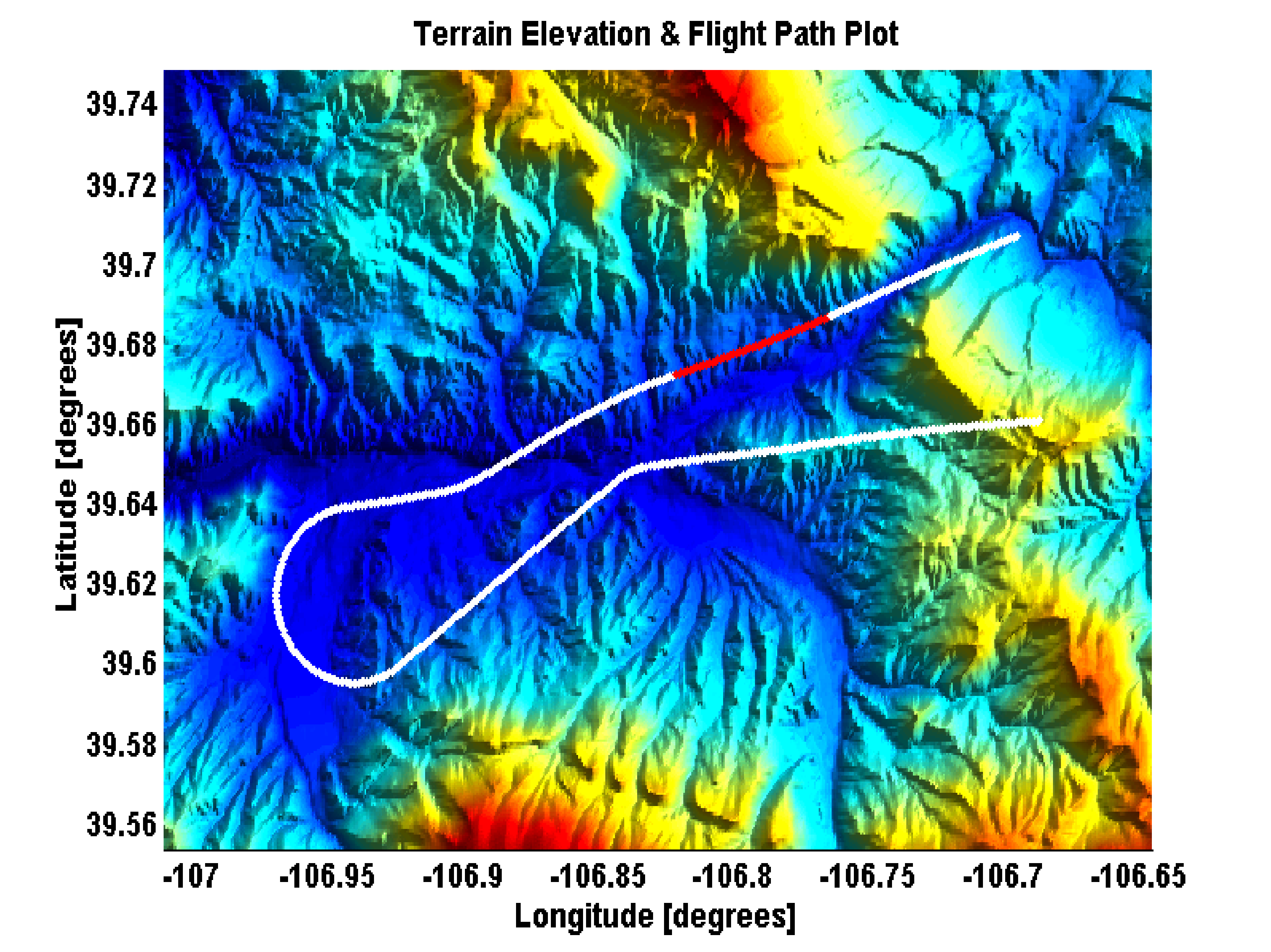
Threshold Diagram



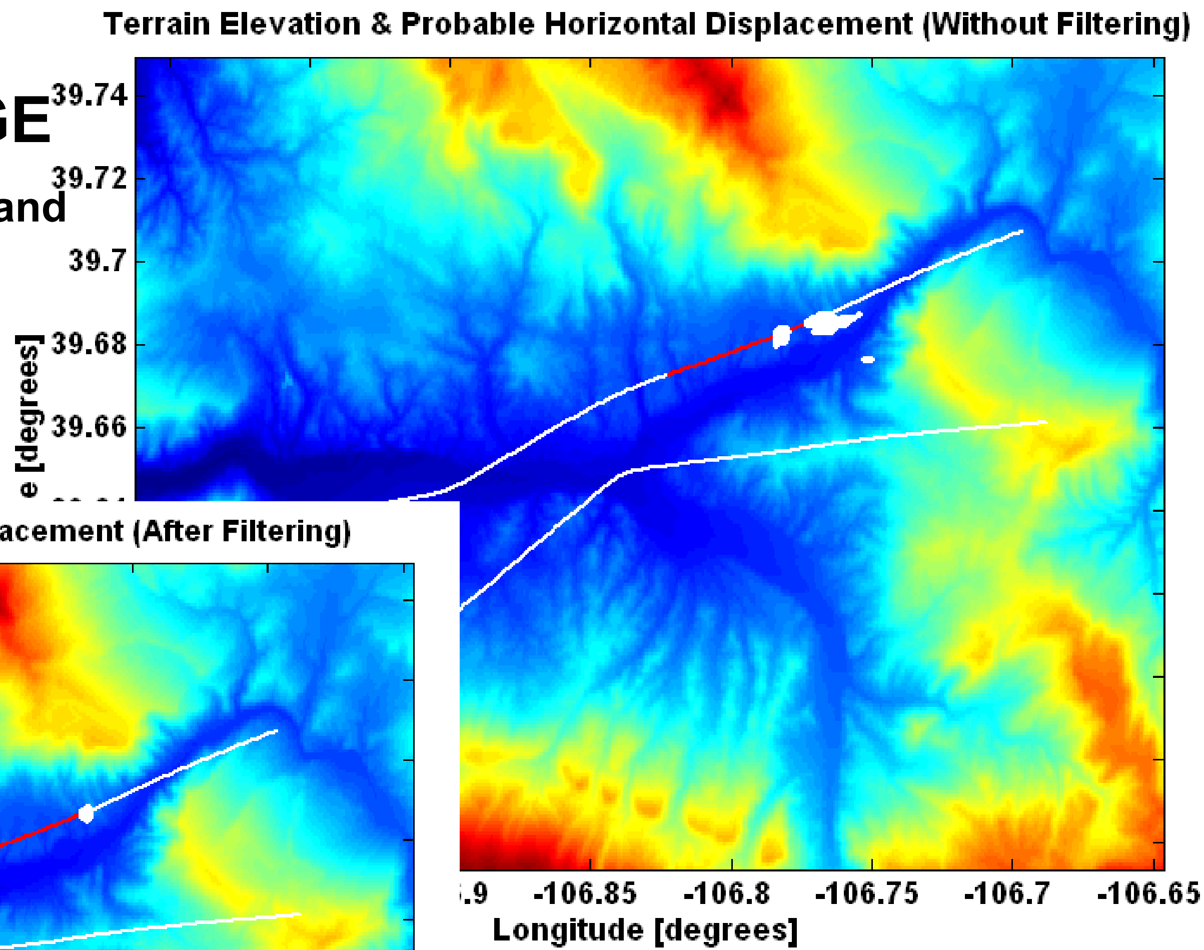


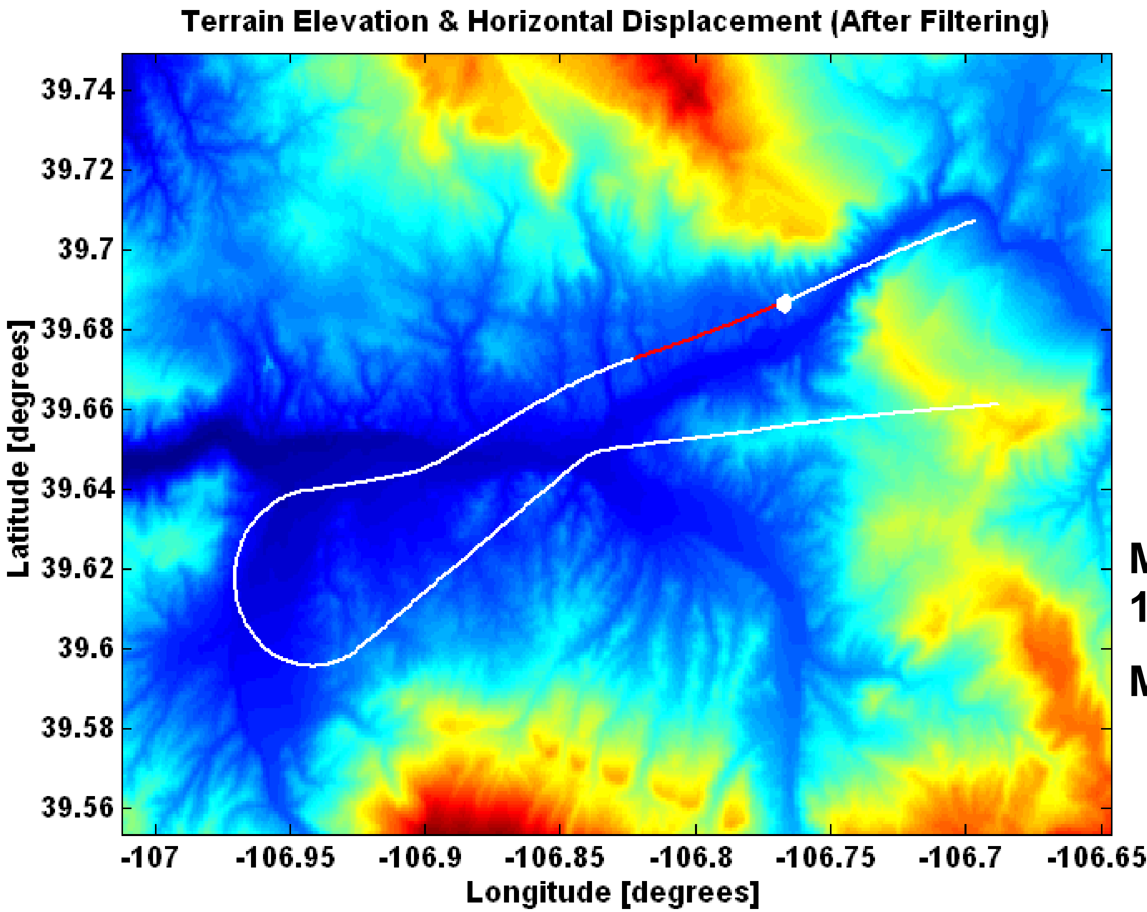

Terrain Elevation & Flight Path Plot
39.74
39.72
39.7
39.68
39.66
39.64
39.62
39.6
39.58
39.56
Latitude [degrees]
-107
-106.95
-106.9
-106.85
-106.8
-106.75
-106.7
-106.65
Longitude [degrees]

Approach to R/W 7, EGE

Minimum T offset = 92.6 m South and 0 m West

Maximum Displacement = 1,865 m

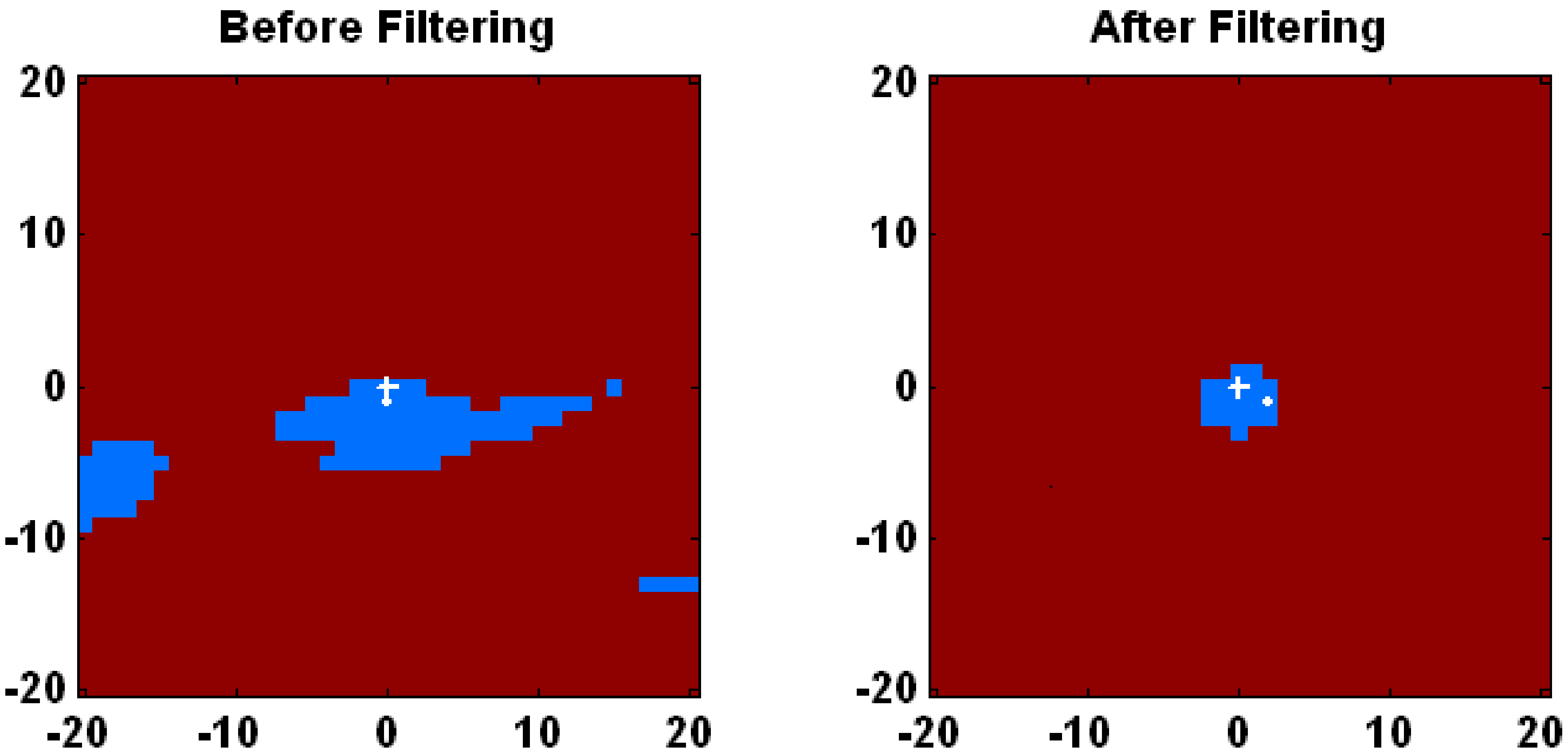




Minimum T offset = 92.6 m South and 142 m West

Maximum Displacement = 163 m

Threshold Diagram



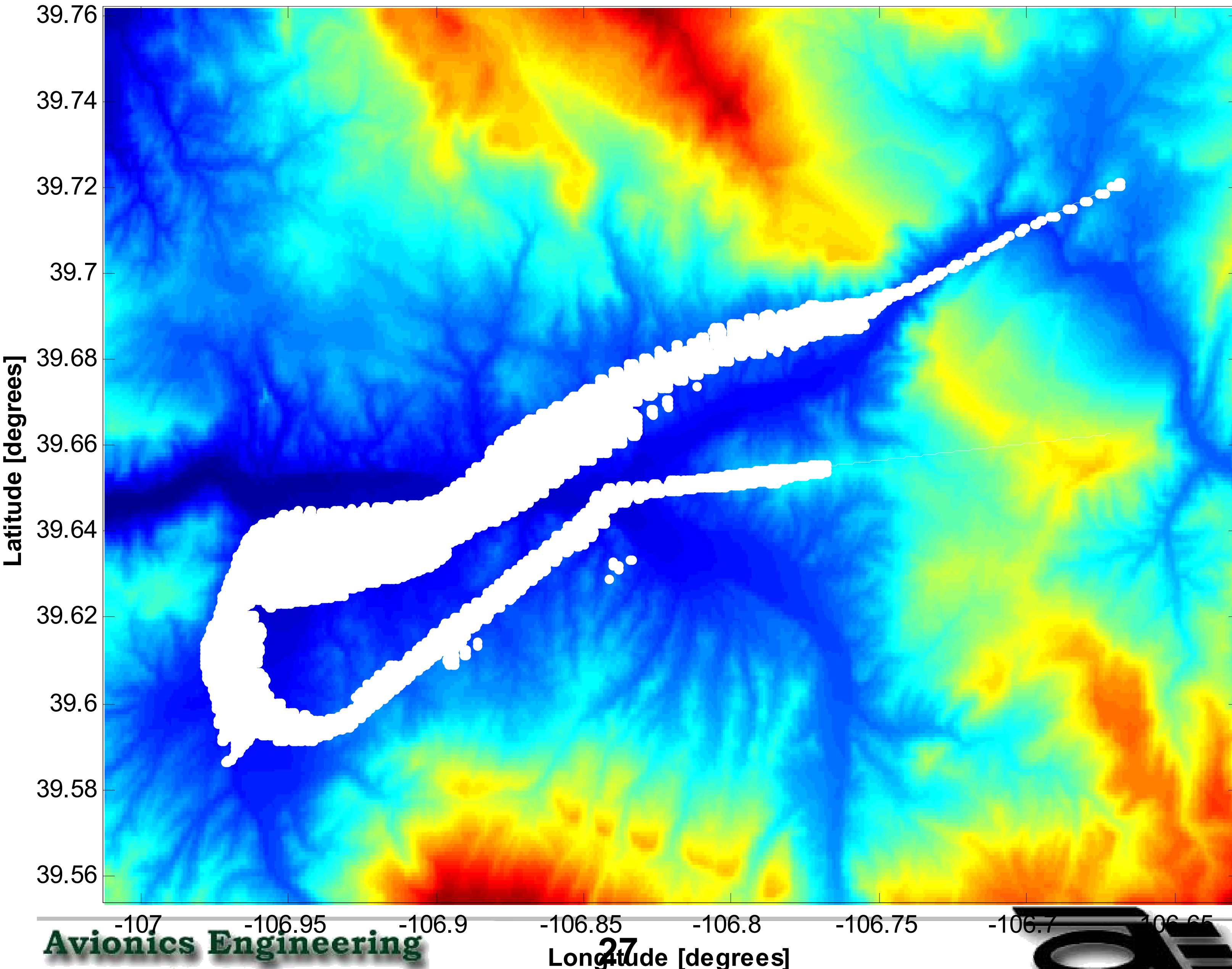
Information Content of the Terrain

$$I = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(\Delta h_{synth}\right)^2}$$

$$I = \sqrt{\frac{1}{N}\sum_{i=2}^{N}\left(h_{synth}(i) - h_{synth}(i-1)\right)^2}$$

The performance of the Horizontal Integrity Monitor directly depends upon the Terrain Signature

Region of Missed Detection (Unfiltered)



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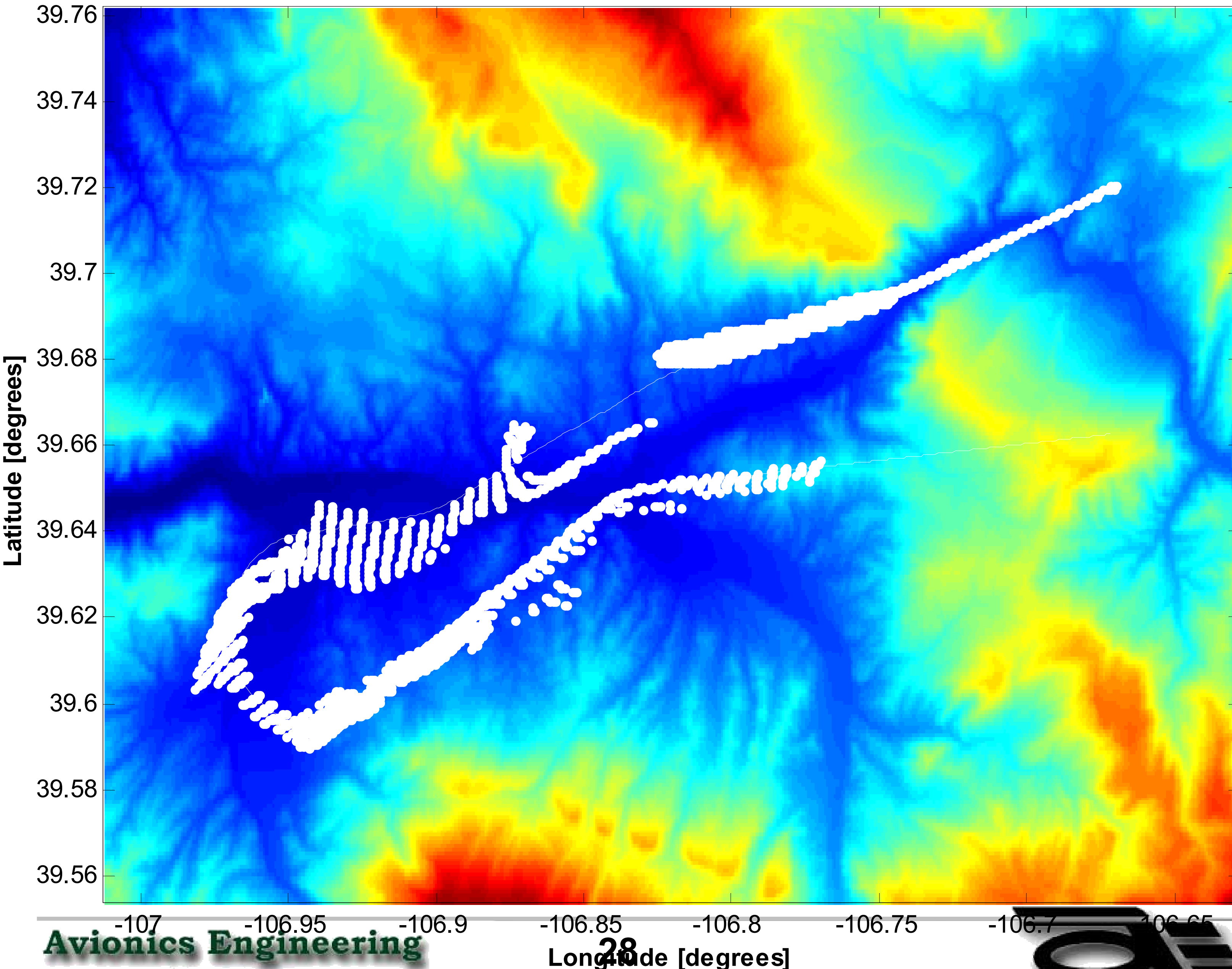
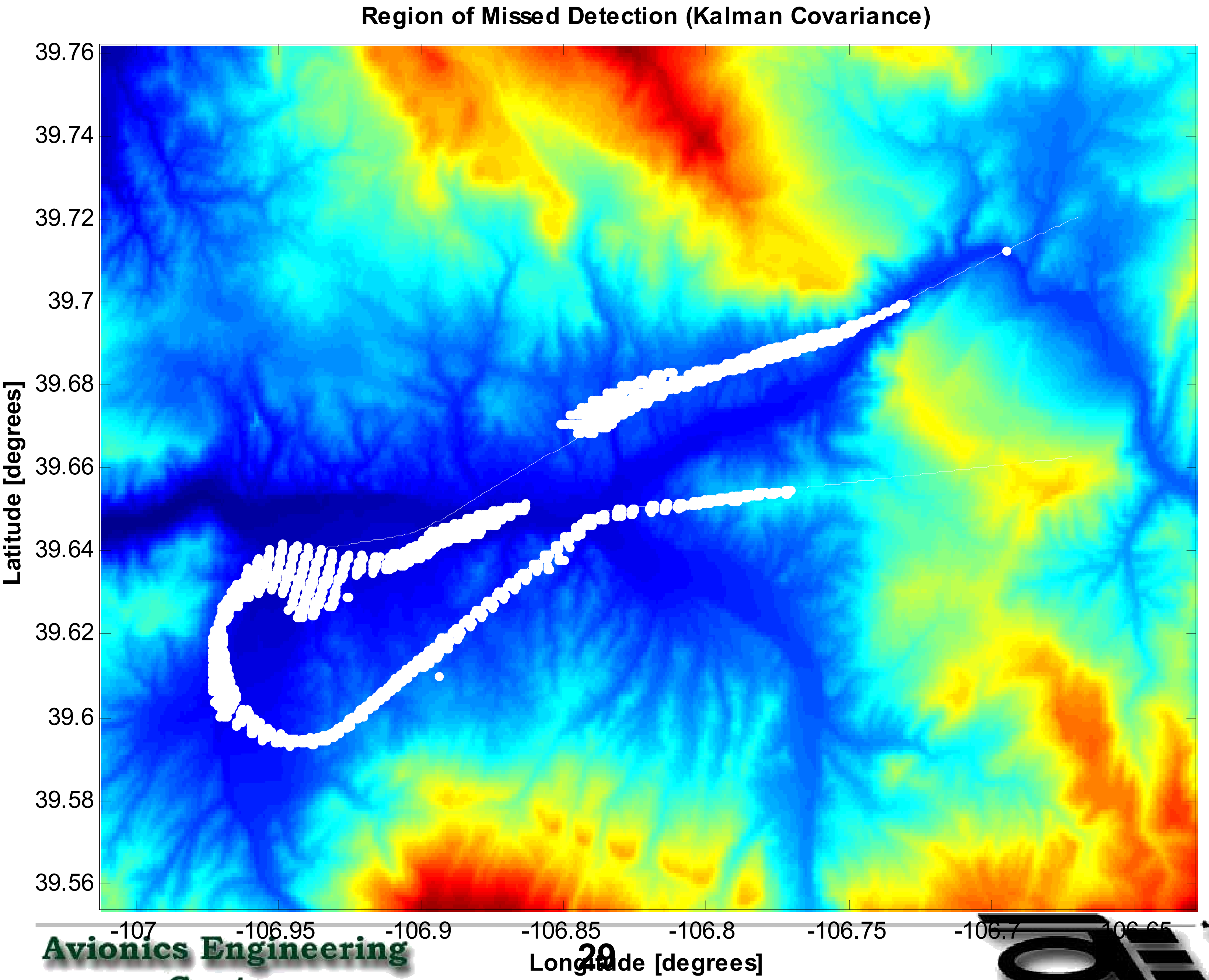
Region of Missed Detection (LS)





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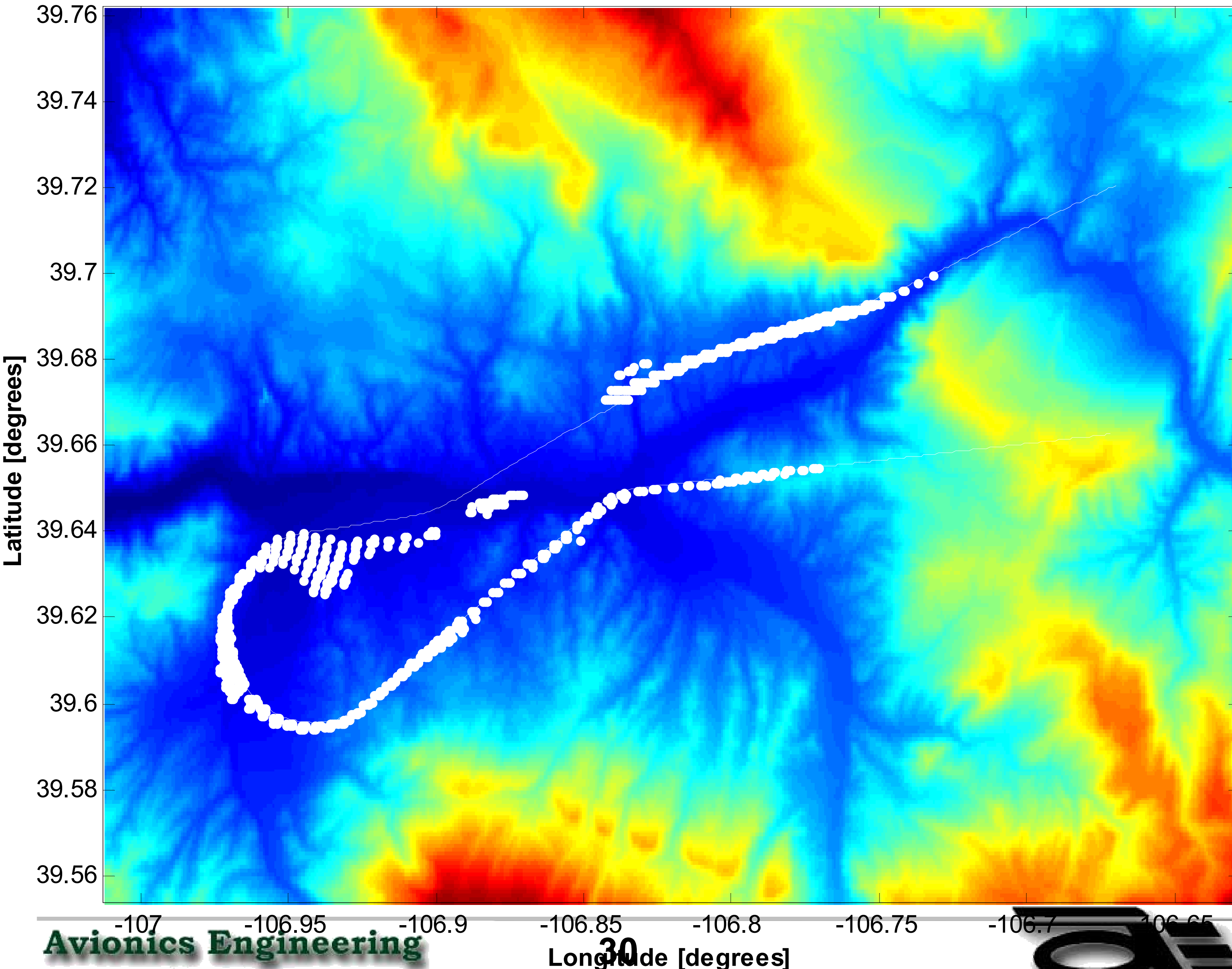
Region of Missed Detection (Kalman Monte Carlo)



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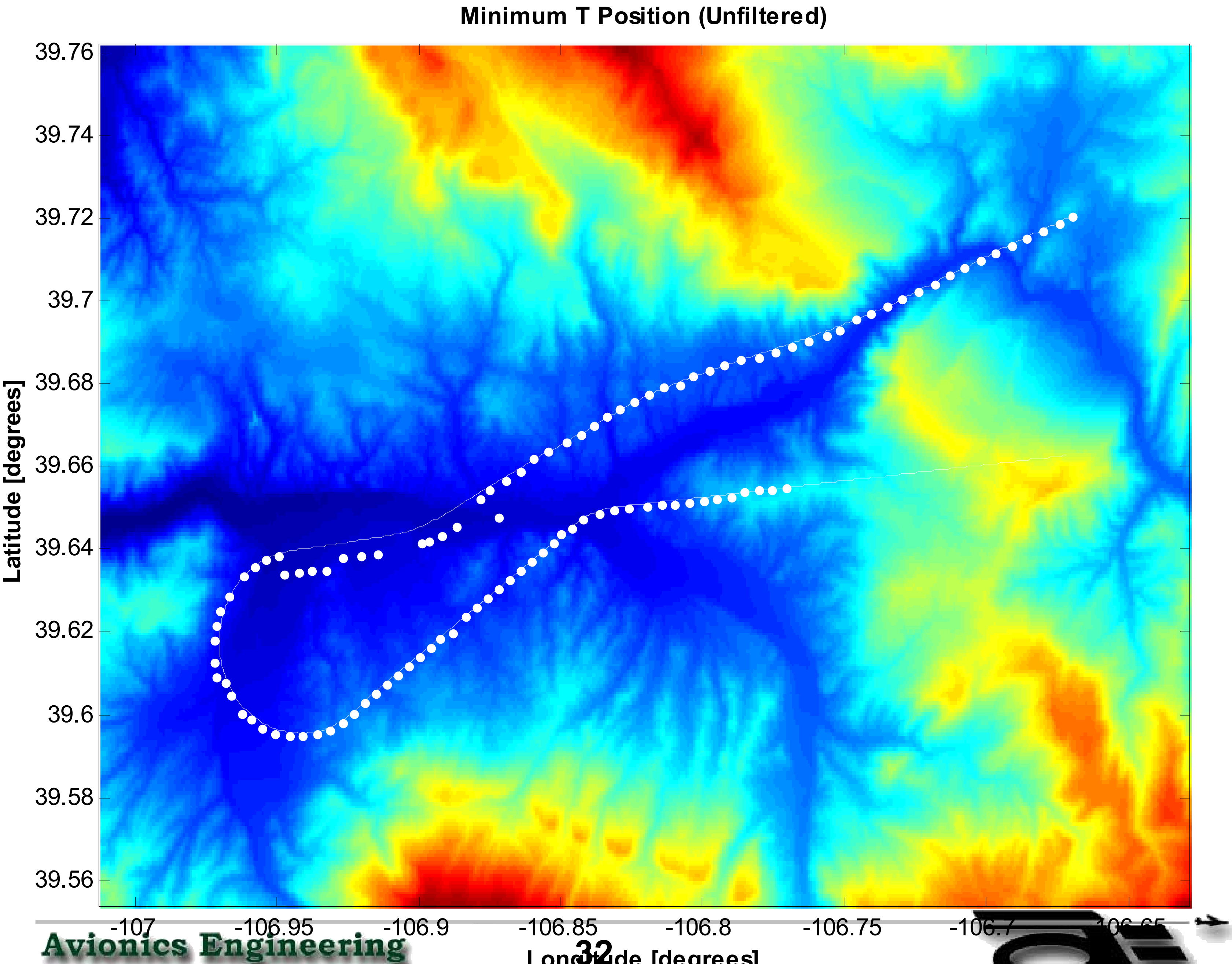
Terrain Navigation

- The ‘T’ statistic can also be used for Terrain Navigation. a.k.a Map-aided Navigation
- It is a measure of the agreement of the synthesized and database terrain profiles
- Minimum T position ~ Maximum agreement

Military examples of terrain navigation: TERCOM, SITAN



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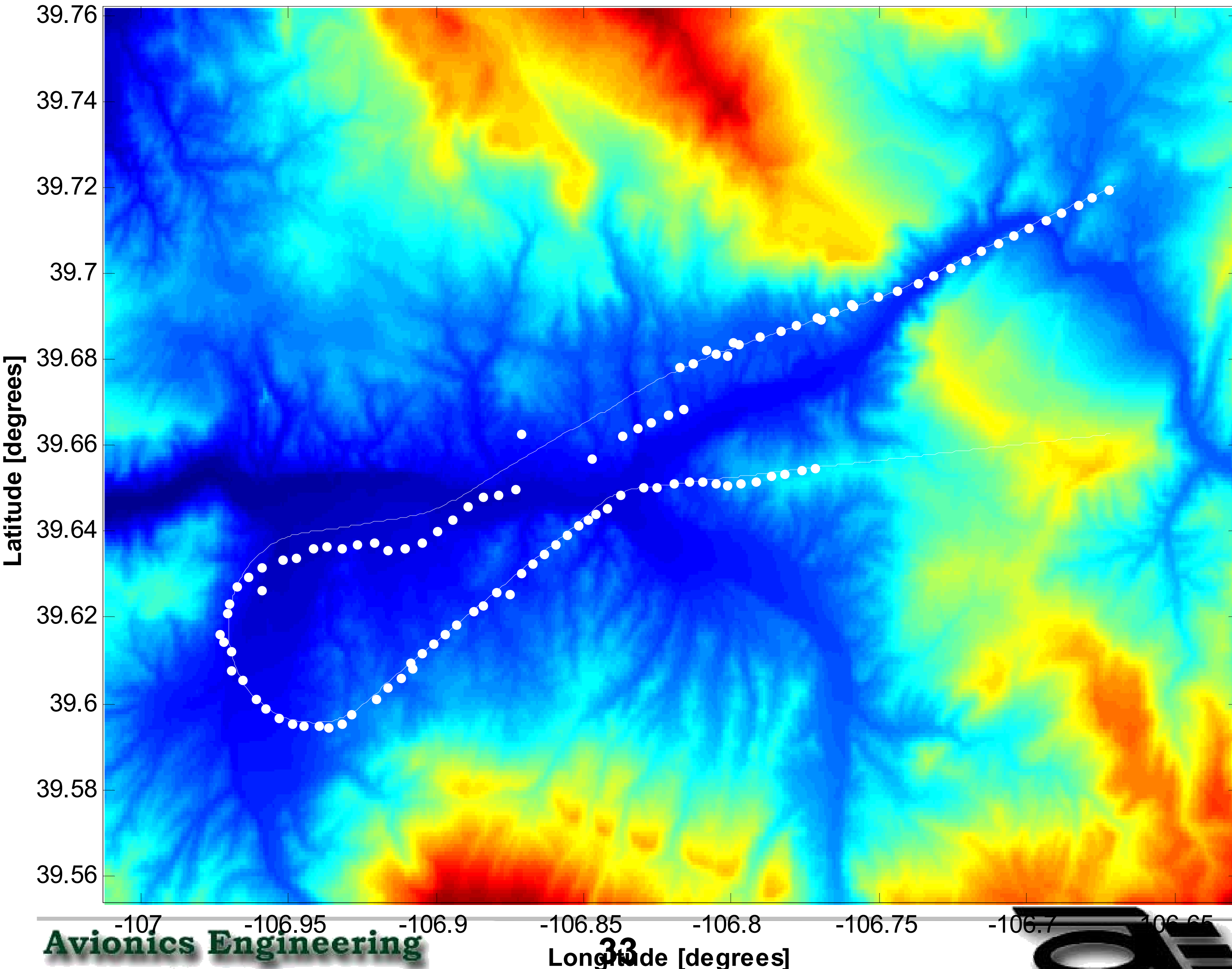
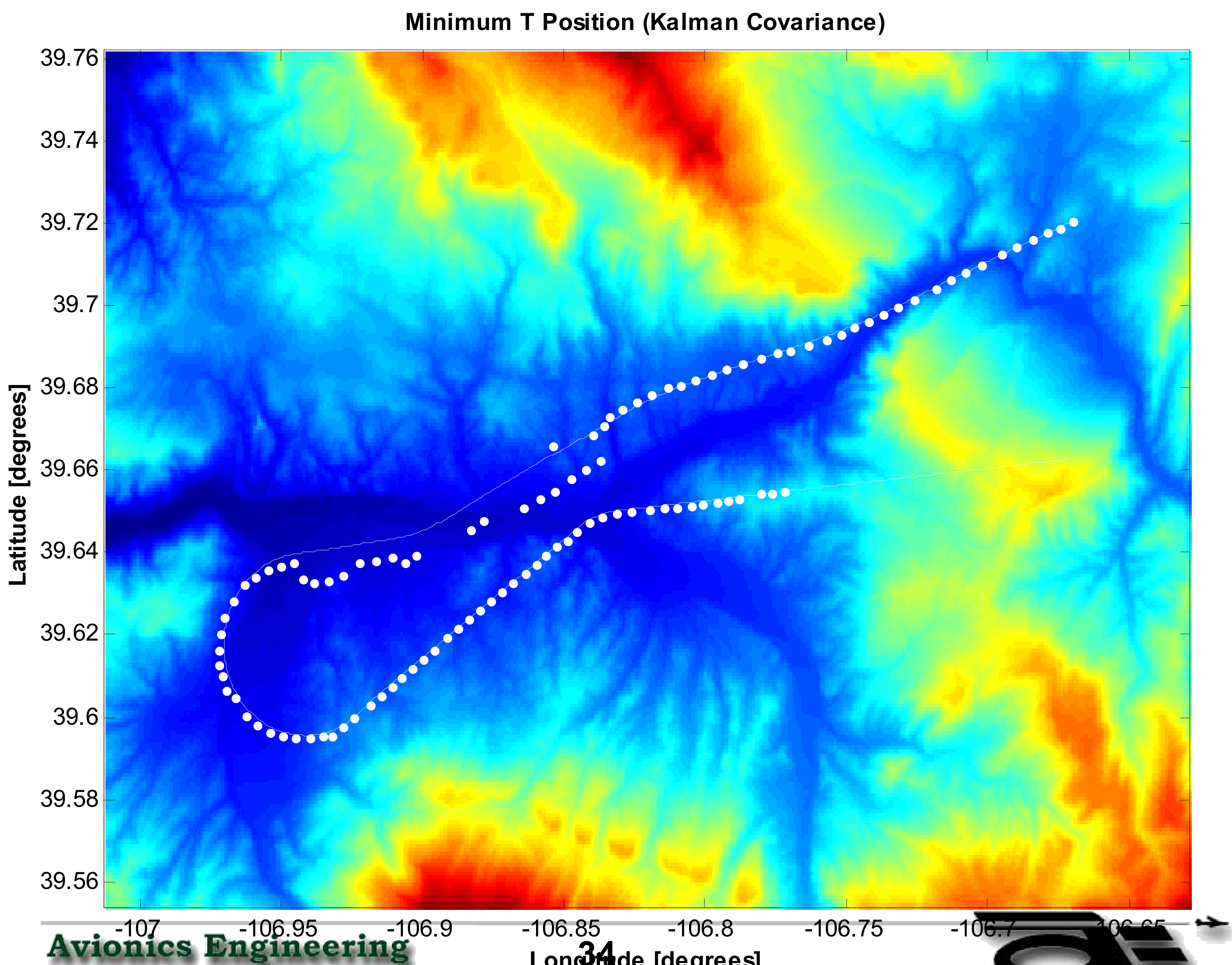
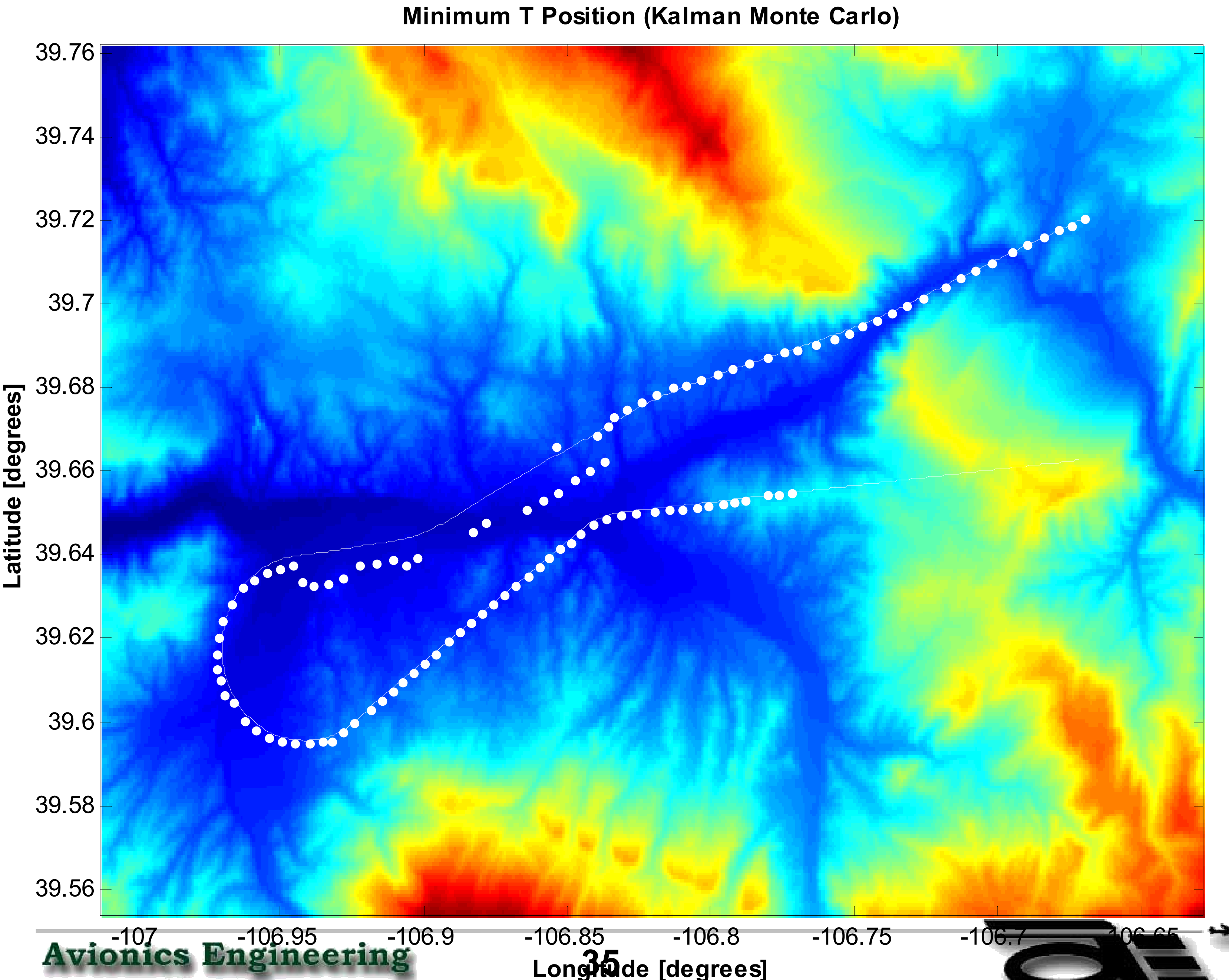
Minimum T Position (Least Squares)





Minimum T Position (Kalman Covariance)
39.76
39.74
39.72
39.7
39.68
39.66
39.64
39.62
39.6
39.58
39.56
Latitude [degrees]
-107
-106.95
-106.9
-106.85
-106.8
-106.75
-106.7
-106.65
Longitude [degrees]



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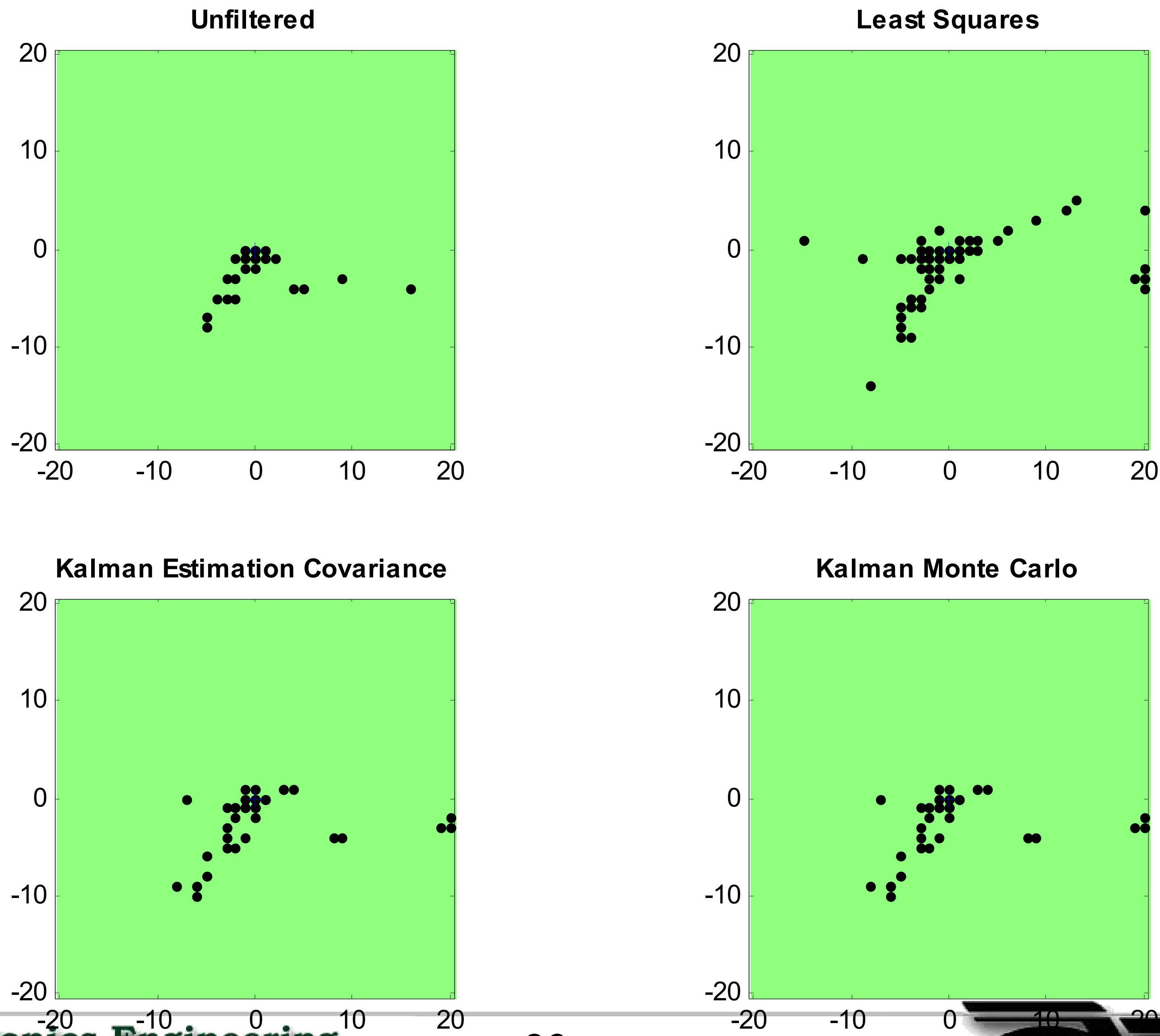
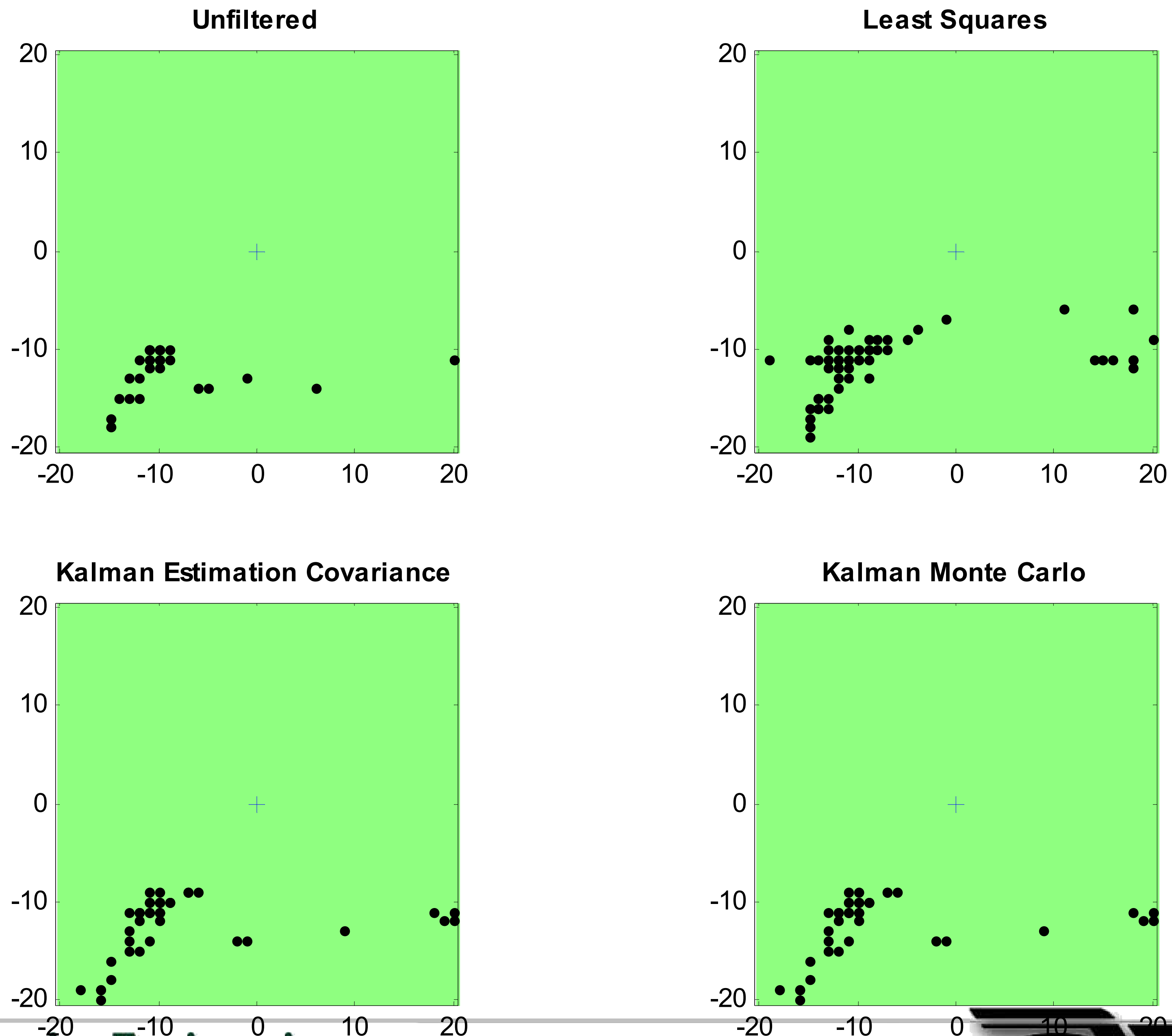

Unfiltered
Least Squares
Kalman Estimation Covariance
Kalman Monte Carlo
20
10
0
-10
-20
-20
-10
0
10
20


Unfiltered
Least Squares
Kalman Estimation Covariance
Kalman Monte Carlo
20
10
0
-10
-20
-20
-10
0
10
20

Conclusions and Continuing Research

- Kalman filter improves the statistical estimation capability for terrain database integrity monitoring, and its potential yet to be explored for terrain navigation
- Development of an algorithm that would perform well when the aircraft undergoes a sharp turn
- Kalman filtering could be applied in a dynamic case to reduce the noise on the sensor measurements
- The next step is to go from estimation to detection that would allow the vehicle to navigate autonomously
- The integrity monitor could help SVS to meet reliability requirements for safety critical certification levels

References

1. Campbell, J.,”Characteristics of a real-time digital terrain database integrity monitor for a synthetic vision system, MS thesis, Department of Electrical and Computer Engineering, Ohio University, Athens, Ohio, November 2001.

2. Gray, R.A., “Inflight Detection of Errors for Enhanced Aircraft Flight Safety and Vertical Accuracy Improvement using Digital Terrain Elevation Data With an Inertial Navigation System, Global Positioning System and Radar Altimeter”, Ph.D. Dissertation, Department of Electrical and Computer Engineering, Ohio University, Athens, Ohio, 1999.

3. Brown, R. G and Hwang, P.Y.C., Introduction to Random Signals and Applied Kalman Filtering, John Wiley & Sons, 1997

4. Uijt de Haag, M., Campbell, J., Gray, R.A., “A Terrain Database Integrity Monitor for Synthetic Vision Systems”

5. Bergman, N., Ljung, L. and Gustafsson, F., “Terrain Navigation using Bayesian Statistics”