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Integrity Monitoring for Reliable Positioning in Cooperative Intelligent Transport Systems

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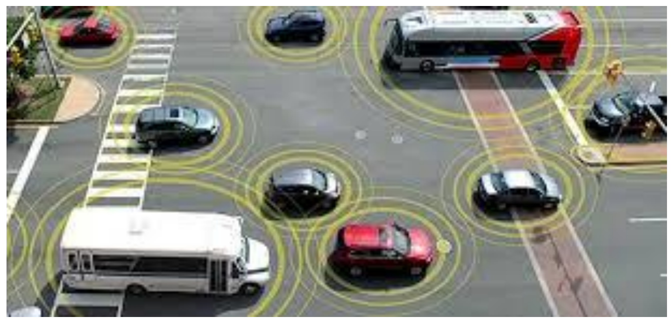
Contents

C-ITS

Cooperative Intelligent Transport Systems (C-ITS) deliver innovative services that will enable greater safety, savings in journey times, and reduced traffic congestion



New technologies are likely be added to existing systems Industry may adapt V2X / Connected Vehicle technology as an add-on

Challenges unique to automotive

Design driven by styling, cost and complexity
Automotive design cycle is typically 3-4 years & design life is around 8 years*
Significant work is needed to widely utilize Over-the-Air (OTA) update capability

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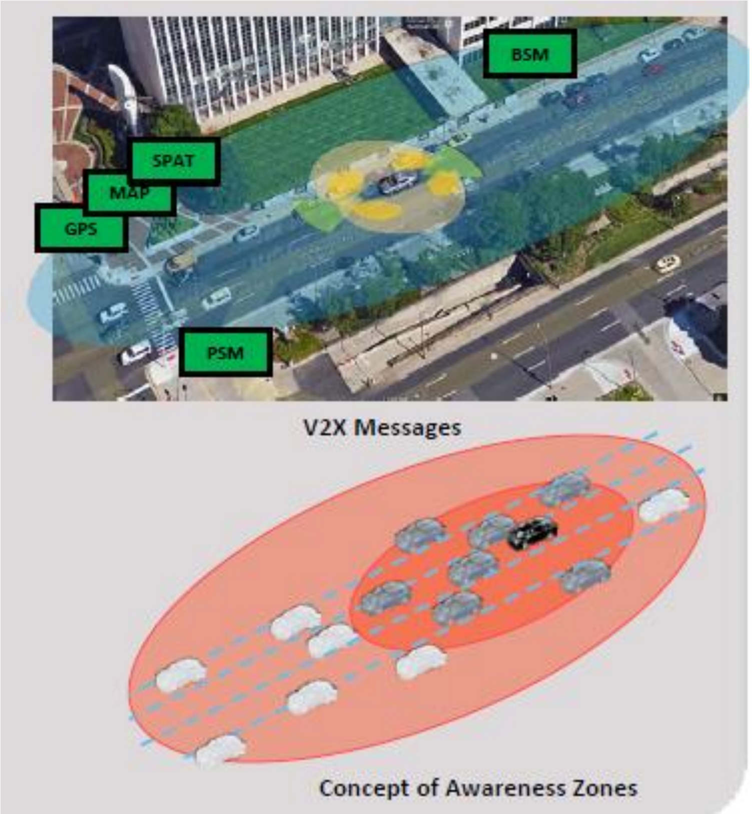
Concept of Operation **V2X (V2V, V2I and V2P)**

Concept of Operation

Vehicles broadcast absolute position & time Classify vehicles as: Traveling in same direction, opposite or other

Same lane or adjacent lane

- Identify threats & generate warnings

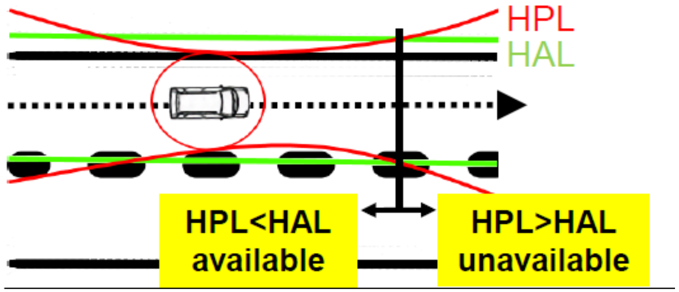


Typical accuracy requirements

- Road level: better than 5 m absolute
- Lane level: better than 1.5 m absolute
- **Minimum performance requirements for V2X vehicle / onboard equipment (SAE 2945/1), On-Board System Requirements for V2V Safety Communications, http://standards.sae.org/j2945/1_201603/**
- **•Over-the-Air (OTA) message specification for V2X (SAE J2735), Dedicated Short Range Communications (DSRC) Message Set Dictionary, http://standards.sae.org/j2735_201603/**

Objective

- Precise positioning is a fundamental component of ITS.
- We need to provide continuing, trustworthy and safe positioning.
- the system needs to have a full **integrity monitoring**.



Integrity Monitoring

Definitions:

- Integrity is that quality which relates to the trust which can be placed in the correctness of the information supplied by the total system.
- Integrity includes the ability of a system to provide timely warnings to the user when the system should not be used for the intended operation.
- Integrity risk is the probability of an undetected failure of the specified accuracy.

What is difference between QC and IM?

- IM generally implies a real-time application.

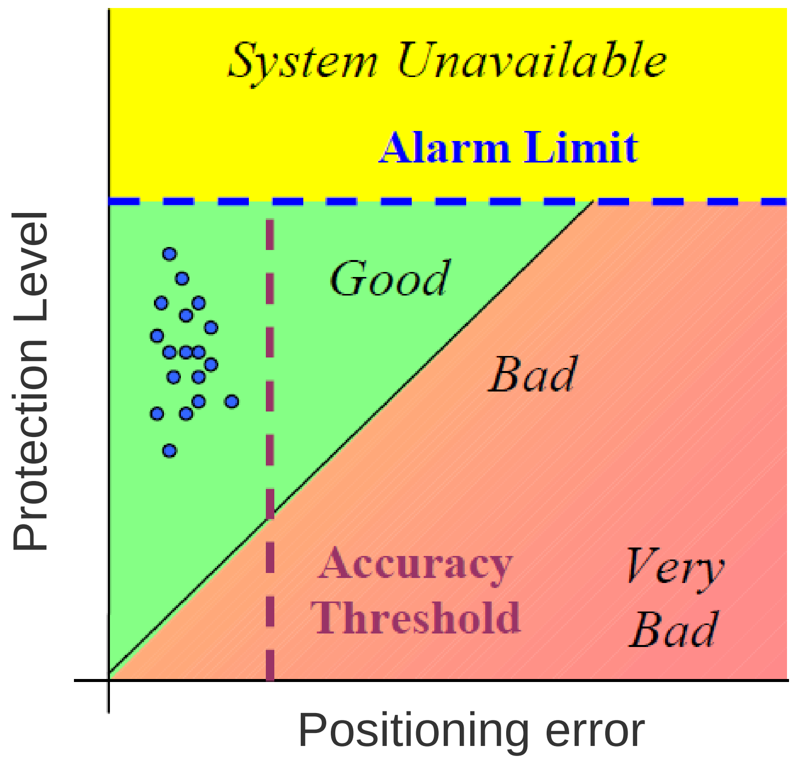
Integrity Monitoring

- Two main tasks:

1- Detection and exclusion of faulty data (**FDE**).

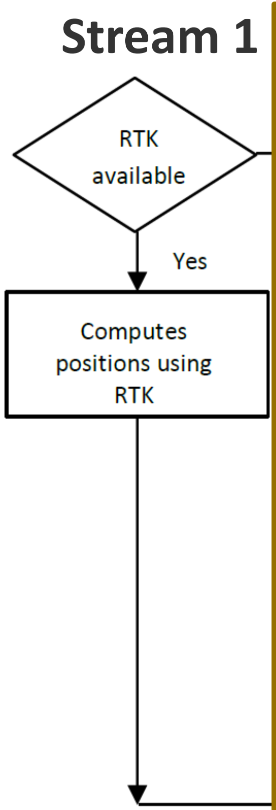
2- Check that system performance meets standards.

(Accuracy, reliability, continuity and integrity)



Positioning System (RTK /IMU/Speedometer)

A system capable of maintaining positioning during periods of GNSS blockage; e.g. urban environments or when passing through tunnels.



Positioning continuity using RTK /IMU/speedometer

Conditions

Stream 1

Low-cost RTK
Provides cm accuracy

Stream 2

Doppler
Err: sub-m to 1 m
update < 1 min

- HDOP < 1.5;
- $|V_{GNSS} - V_{SS}| < 0.5$ m/s

Stream 3

MEMS IMU/SS
Err: < 2 m
Within 20 sec

GNSS calibrate IMU
- HDOP < 2.5
- $|V_{GNSS} - V_{SS}| < 1.5$ m/s
- $V_{SS} > 0.5$ m/s
  or ZUPT

Observation models

A fault-free mode

$$y = G\,x + \; b + \; \varepsilon$$

H_0 is: E{y}= $G\,x + b$, D{y} = $Q_{y,}$

with faults

$$y = G\,x + \; G_f \nabla + b + \; \varepsilon$$

H_a: E{y}= $G\,x + \; G_f \nabla + b$, D{y} = Q_y

$$1 \leq q \leq df$$

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Integrity monitoring

i. FDE

- ***Detection of faulty observations***

$$\hat{e}^T\, Q_y^{-1}\, \hat{e} \geq \chi^2_\alpha(df_i, 0)$$ (UMPI - Chi-square test)

- ***Exclusion of faulty observations***

$$|\hat{x} - \hat{x}_i| > T_i$$ (solution separation method)

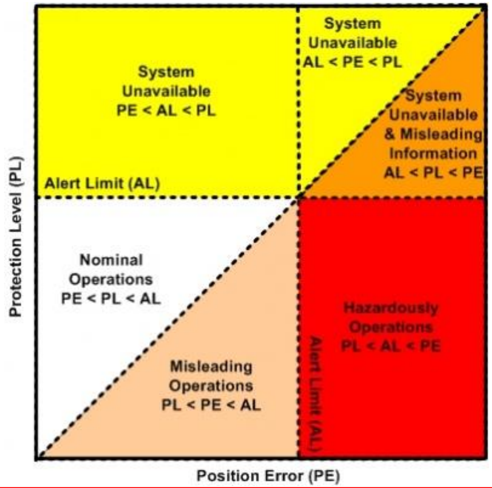
Confirm exclusion

$$\hat{e}^T\, A_i\, Q_y^{-1}\, \hat{e} \geq \chi^2_\alpha(df_i, 0)$$

$$|w_j| \geq N_{\frac{\alpha}{2}}(0,1) \qquad |w_i| \geq |w_k| \qquad \text{for } k = 1 \text{ to } m$$

ii. Integrity checks

- *HPE < HPL*
- *HPL < HAL*



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RTK integrity RISK

* $P(|dx_H| \geq HPL) \geq P(I)_H$

* $P(|dx_v| \geq VPL) \geq P(I)_V$

$$P(I)_H = P(|dx_H|_o \geq HPL_o|\ CF) \times PCF \times P_{m_{d_{mode1}}}$$
$$+P(|dx_H|_o \geq HPL_o|\ IF) \times PIF \times P_{m_{d_{mode2}}}$$
$$+ \sum_{i=1}^{m} P(|dx_H|_i \geq HPL_i|\ IF) \times PIF \times P_{m_{d_{mode3}}}$$

Miss-detection

Mode 1: ambiguities are correctly fixed (PCF).
Mode 2: ambiguities are incorrectly fixed (PIF) using all sats
Mode 3: ambiguities are incorrectly fixed (PIF) excluding satellite i.

PIF = 1 - PCF

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RTK Protection Levels

- A new HPL metric: for the maximum direction error - the semi-major axis of a confidence error ellipsoid

$$HPL_{\zeta,i} = K_{fa_{(H)_{max},i}}\ \sigma_{dH_{max},i} + K_{md_{max},i}\ \sigma_{H_{max},i}$$

$$HPL_i = K_{fa_{(H)},i} \sqrt{\sigma^2_{dE,i} + \sigma^2_{dN,i}} + K_{md,i} \sqrt{\sigma^2_{E,i} + \sigma^2_{N,i}}$$

$$VPL_i = K_{fa_{(V)},i}\ \sigma_{dV,i} + K_{md,i}\ \sigma_{V,i}$$

$$\beta = \frac{P(I)_H}{\{P(|dx_H|_o \geq HPL_o|\ CF)\times PCF + P(|dx_H|_o \geq HPL_o|\ IF)\times PIF + \sum_{i=1}^{m} P(|dx_H|_i \geq HPL_i|\ IF)\times PIF}\}$$

$$K_{fa(H),i} = -Q^{-1}\left(\frac{\alpha}{2m}\right), \quad \mathrm{K_{md,i}} = -\mathrm{Q}^{-1}(\beta))$$

$$K_{fa_{(H)_{max},i}} = \sqrt{-2 \times ln(\alpha)}, \quad K_{md_{max},i} = \sqrt{-2 \times ln(\beta)}$$

Doppler-based and IMU/SS Protection Levels

$$HPL_{\zeta,i} = K_{md_{max,i}} \; \sigma_{H_{max,i}} + \cos\,(\theta - \zeta)\,\mathrm{B}_i$$

$$HPL_i = K_{md,i} \sqrt{\sigma_{E,i}^2 + \sigma_{N,i}^2} + \mathrm{B}_i$$

Bias for Doppler

$$\mathrm{B}_i = \sqrt{(a_1^T\, S \begin{bmatrix} b_{v_E} \\ b_{v_N} \end{bmatrix})^2 + (a_2^T\, S \begin{bmatrix} b_{v_E} \\ b_{v_N} \end{bmatrix})^2}$$

Bias for IMU/SS

$$\mathrm{B}_i = \sqrt{(a_1^T\, S \begin{bmatrix} b_{\theta_{IMU}} \\ b_v \end{bmatrix})^2 + (a_2^T\, S \begin{bmatrix} b_{\theta_{IMU}} \\ b_v \end{bmatrix})^2}$$

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Measuring changes in position affects HPL

$$\begin{bmatrix} E_i \\ N_i \end{bmatrix} = \frac{\Delta t}{2} \begin{bmatrix} 1 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 \end{bmatrix} \begin{bmatrix} v_{E_{i-1}} \\ v_{N_{i-1}} \\ v_{E_i} \\ v_{N_i} \end{bmatrix} + \begin{bmatrix} E_{i-1} \\ N_{i-1} \end{bmatrix}$$

- For Doppler-based and IMU/speedometer positioning:
  The covariance matrix increases with time until updates are provided.

$$Q_{EN_i} = A \; Q_{obs} \; A^T + Q_{EN_{i-1}}$$

Accuracy requirement

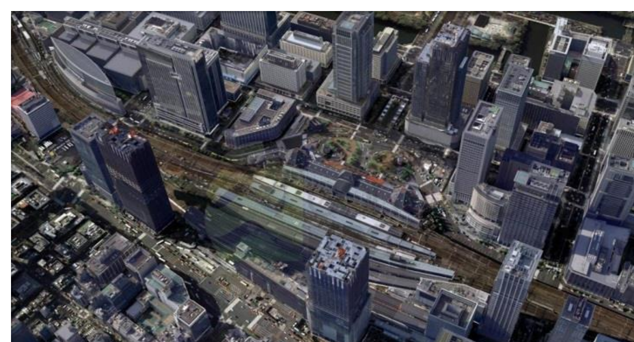
Accuracy (95%) = $K_{acc} \; \sigma_H < threshold,$ where K_{acc} = 1.96.

Testing

- kinematic test in Tokyo
- Trimble RTK (10Hz)
- GPS, GLONASS and BeiDou
- a Bosch-consumer grade MEMS IMU

  The heading error of this IMU ranged from -2^{o} to 5^{o}, can accumulate to 10^{o} after 30 min if left uncalibrated.

- Speed sensor (SS): σ = 5 cm/s
- GNSS-Doppler: σ = 10 cm/s.
- Reference : PPK & POS/LV



RTK Results

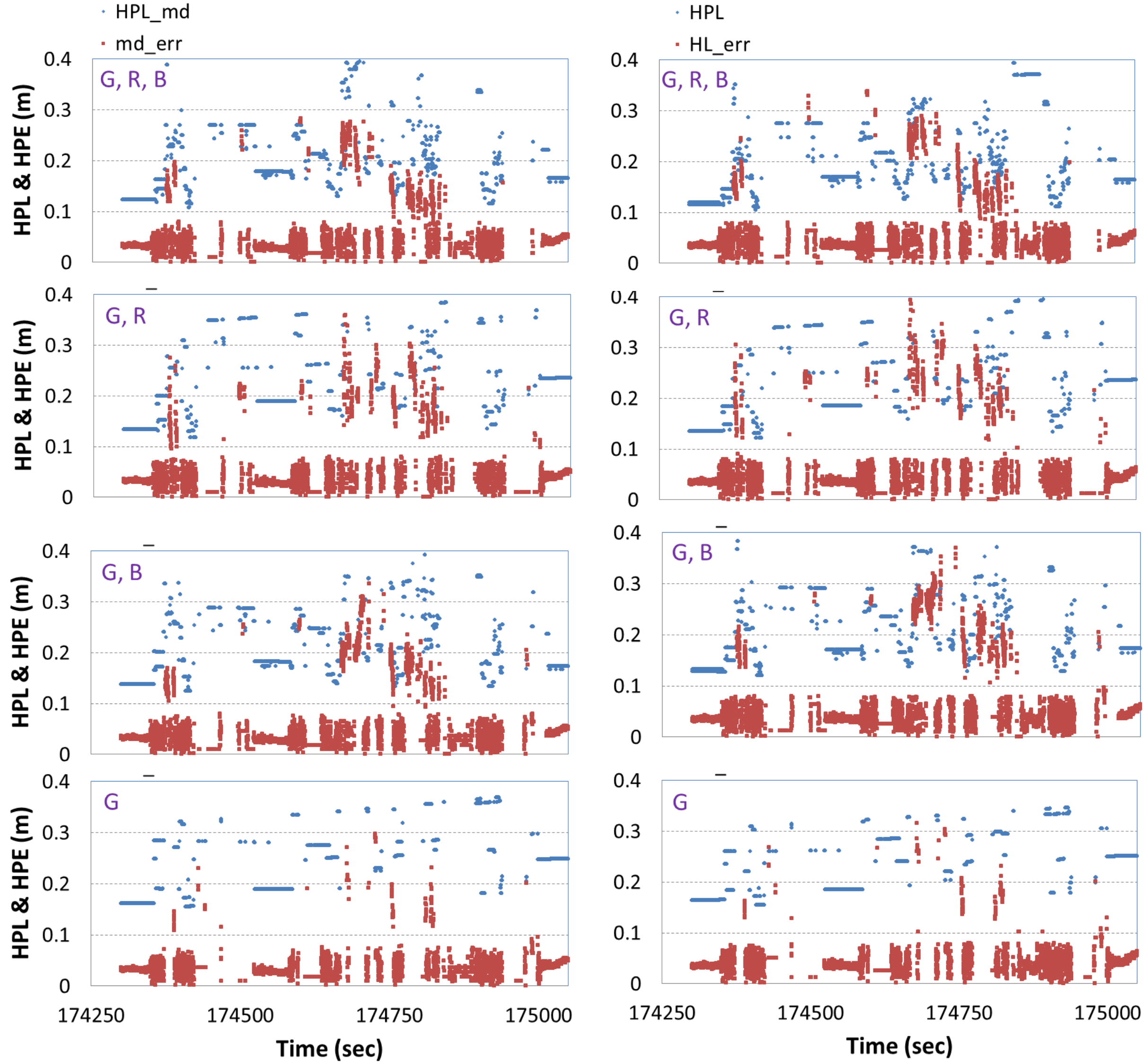
- Use different constellations
- $\beta = 1\times10^{-4}$

G+R+B

G+R

G+B

G



RTK Results

Median **HPL** - different integrity risk probabilities (m)

β	1×10^{-2}	1×10^{-3}	1×10^{-4}	1×10^{-5}	1×10^{-6}	1×10^{-7}
G+R+B	0.102	0.136	0.164	0.188	0.210	0.228
G+R	0.116	0.146	0.186	0.212	0.236	0.258
G+B	0.108	0.144	0.172	0.198	0.220	0.240
G	0.132	0.172	0.208	0.232	0.264	0.290

Median **HPL**$_{md}$ (m)

β	1×10^{-2}	1×10^{-3}	1×10^{-4}	1×10^{-5}	1×10^{-6}	1×10^{-7}
G+R+B	0.086	0.106	0.122	0.138	0.150	0.162
G+R	0.134	0.164	0.190	0.212	0.232	0.250
G+B	0.128	0.158	0.182	0.204	0.222	0.242
G	0.148	0.182	0.210	0.234	0.258	0.276

More const. ☞ more sats and better geometry ☞ better integrity monitoring

Less β ☞ larger HPL ☞ lower availability of integrity monitoring.

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RTK Results

- The model can be initially validated.
- A few cases where the ambiguity were missed by one or two cycles.

  The HPL adapt and bound this error.
- With correct ambiguity fixing, HAL < 0.5 m.
- RAIM availability > 99% even when using β of 1×10^{-7}.
- HPLs bounding the HPE at the design integrity risk.

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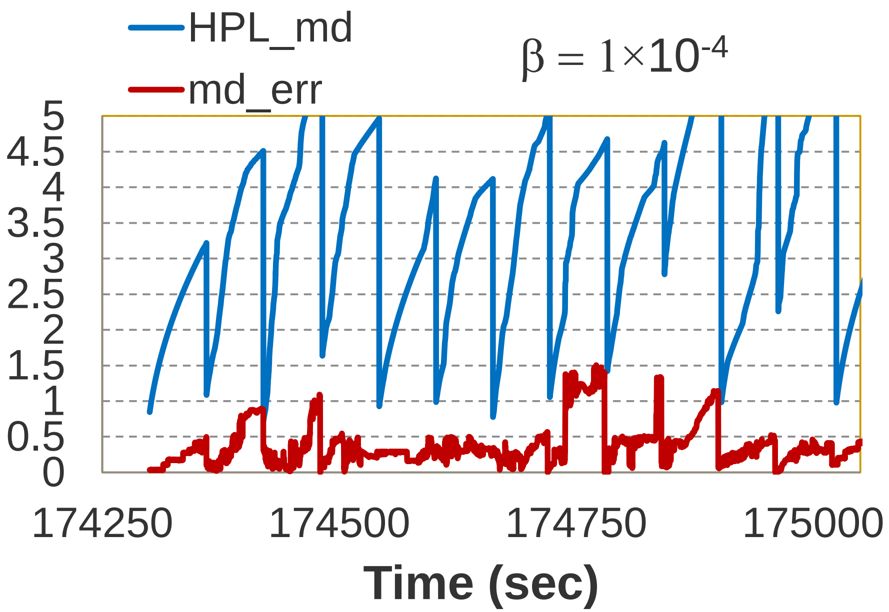
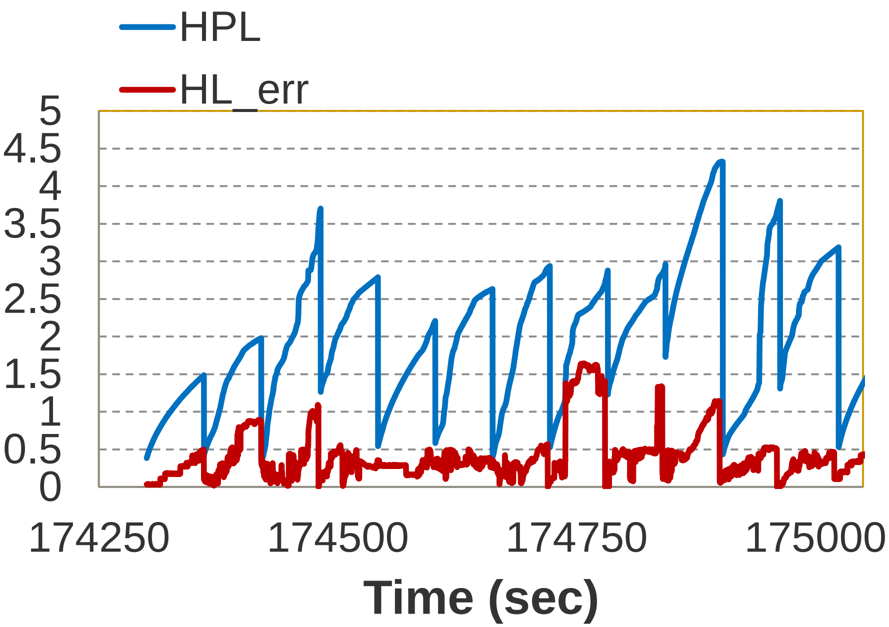
Doppler-based Positioning

- Doppler observations for an extended period of time.
- Reinitialized every 1 min.
- HPL Sawtooth trend: error grow-calibration.
- HPE was bounded by the HPL .





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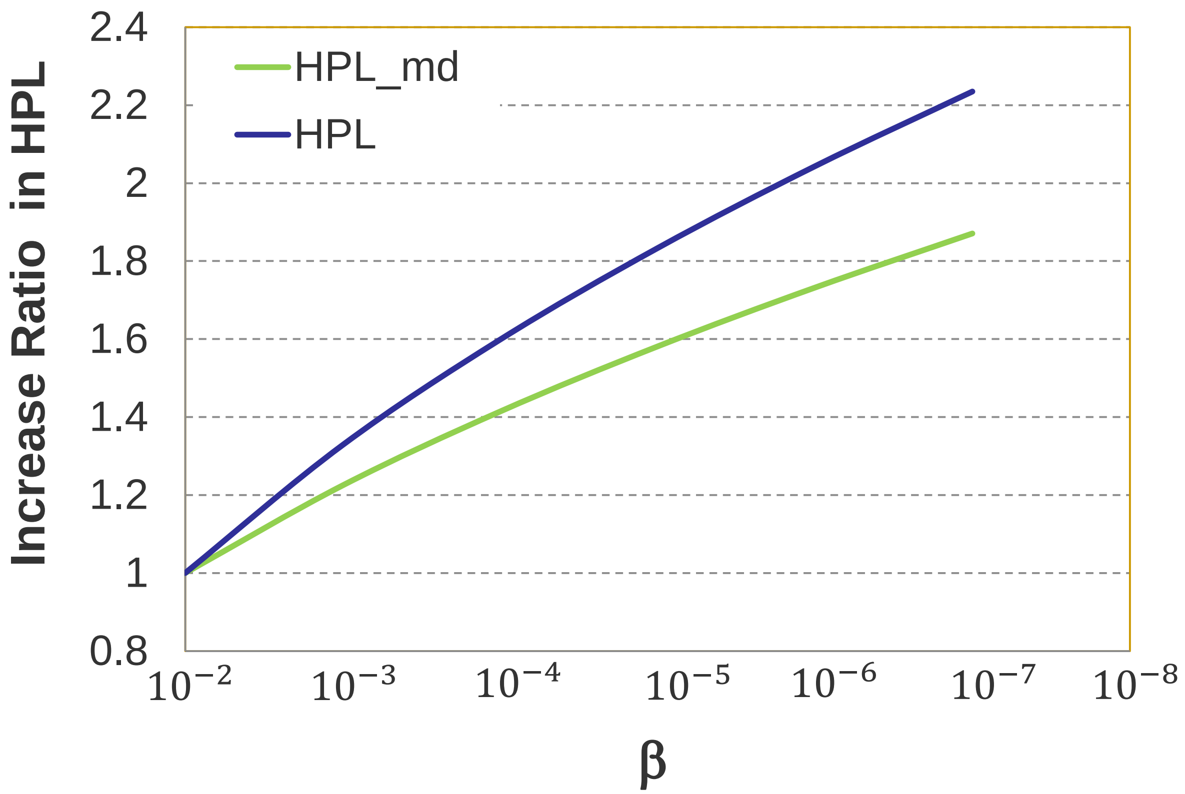
Impact of the allowed probability of integrity risk



- ➢ HPL doubled when integrity risk increased from 1×10^{-2} to 1×10^{-7}

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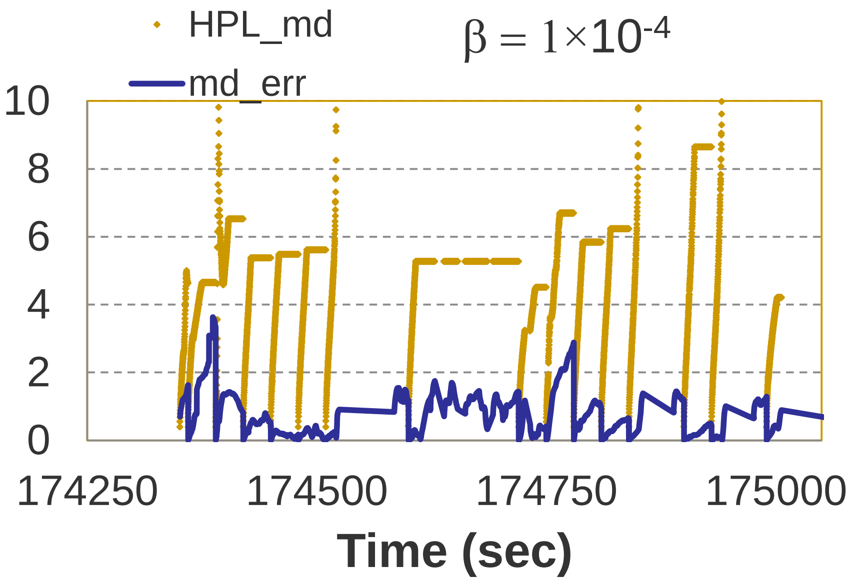
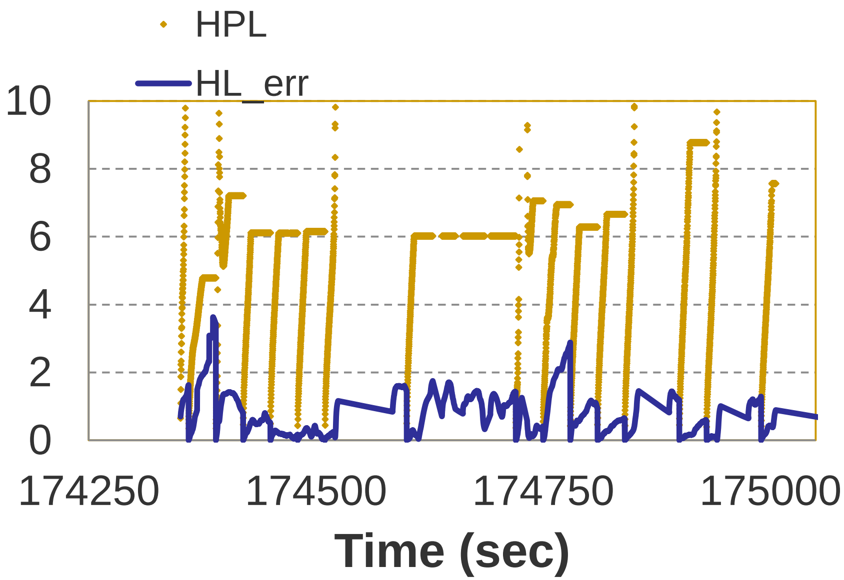
Results of IMU/Speedometer

- The growing heading bias in-between IMU calibrations was the major source that affected the HPL.
- Error > 1.5 m in less than 20 sec after calibration.
- Limited to non-precision car manoeuvring or use a better grade IMU.

$\beta = 1 \times 10^{-4}$





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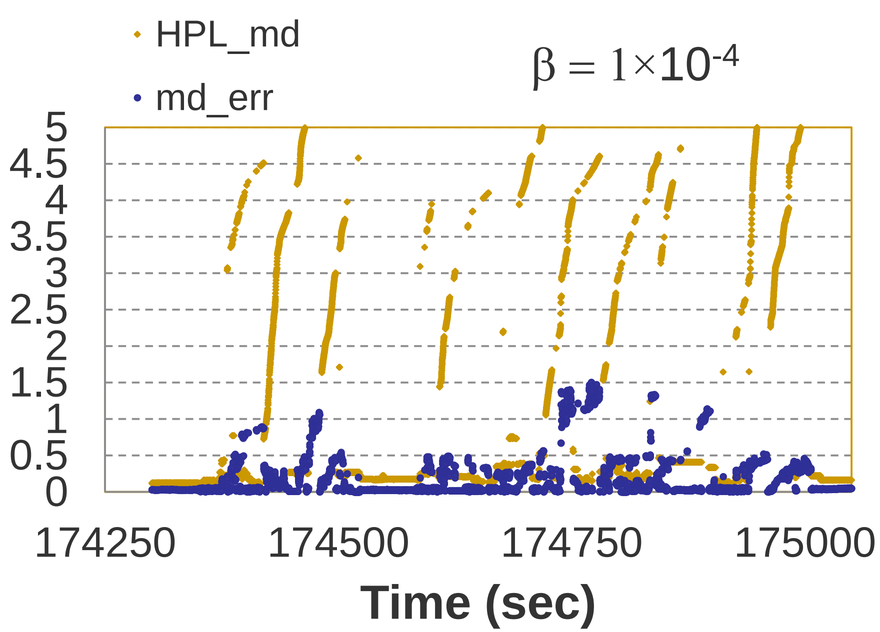
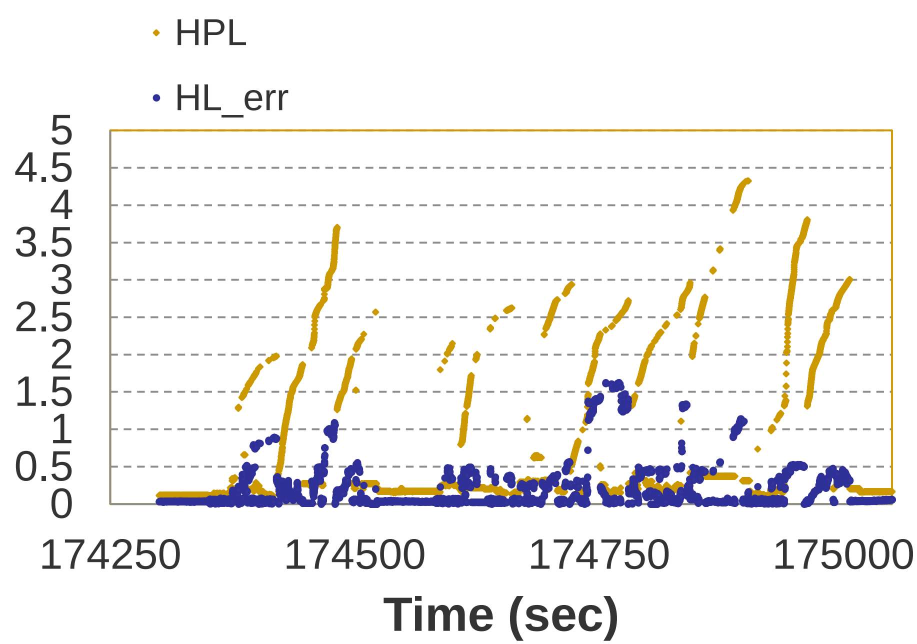
Integrated Systems

- Positioning availability: RTK (72.2%), Doppler-based (25.8%), IMU/SS (2%).
- An overall integrity monitoring availability more than 99% (HPE<HPL<HAL).
- These accuracy capabilities have to be taken into consideration when assigning tasks in ITS.





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Conclusions

- Positioning continuity for C-ITS is proposed using GNSS RTK integrated with low-cost MEMS IMU and automotive sensors.
- To ensure trustworthy positioning New IM models are proposed.
- The use of more constellations, while improves availability of RTK helps in reducing the HPL; and thus, improves availability of IM.
- HAL of 0.5 m can be selected for RTK with
- RAIM availability > 99% .
- Doppler-based or IMU/SS provides positioning can bridge RTK in critical situations, however, they have less integrity & accuracy.

Thank you …

Reflection and Questions