Title
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Publication Date

2019-04-16

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Pseudorange Measurement Outlier Detection for Navigation with Cellular Signals

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Background

- Autonomous ground vehicles (AGVs) will operate in deep urban canyons where global navigation satellite system (GNSS) signals are unusable or unreliable.
- In these environments, signals of opportunity, particularly cellular long-term evolution (LTE) signals are abundant and can be considered as an alternative navigation source in the absence of GNSS signals.

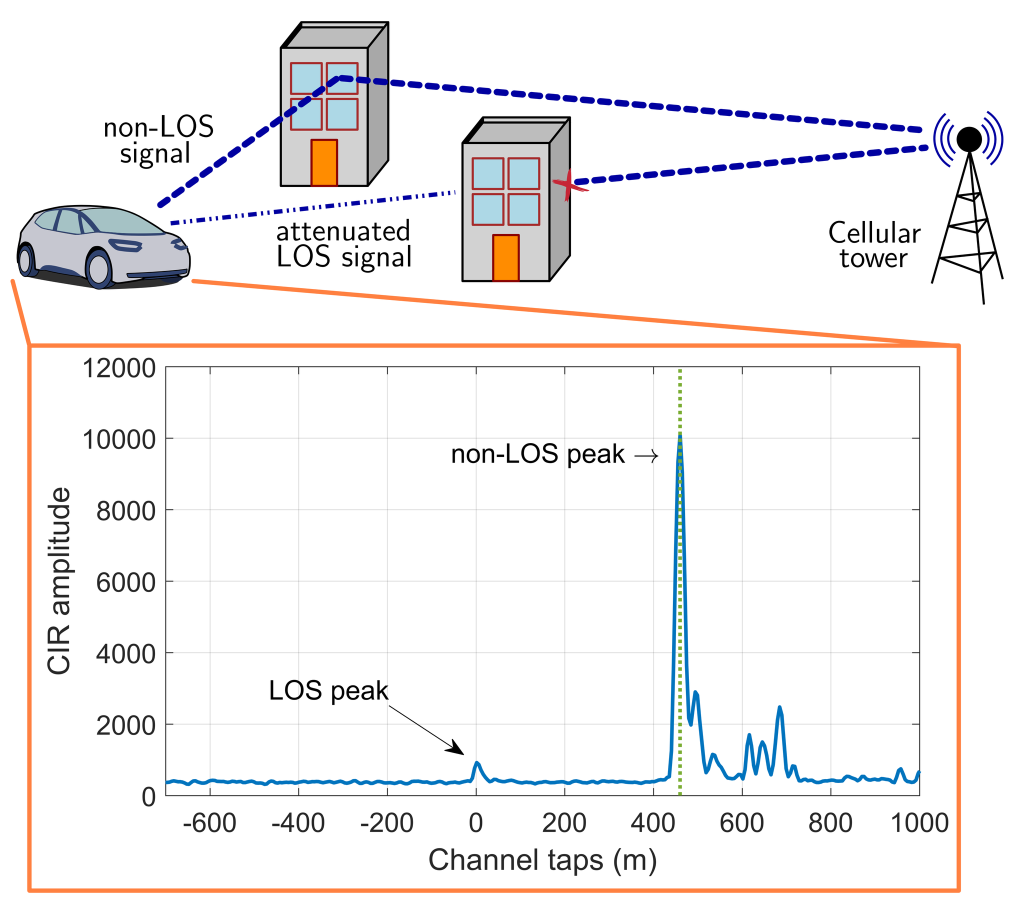
Motivation

- The ASPIN Laboratory has developed proprietary, state-of-the-art receivers and navigation frameworks for AGV navigation with LTE signals, demonstrating meter-level accuracy with standalone LTE signals.
- As the number of systems that rely on cellular signals for navigation grows, the need for monitoring the integrity of their navigation solution becomes essential.

Approach

Developed an autonomous measurement outlier detection and exclusion framework for ground vehicle navigation using LTE cellular signals and an inertial measurement unit (IMU). The proposed framework accounts for:

- line-of-sight blockage
- short multipath delays



State and Measurement

State Model

$$\boldsymbol{x} \triangleq \left[\boldsymbol{x}_v^\mathsf{T}, \boldsymbol{x}_{\text{clk},r}^\mathsf{T}\right]^\mathsf{T}, \quad \boldsymbol{x}_v \triangleq \left[{}^I_G\bar{\boldsymbol{q}}^\mathsf{T}, \; {}^G\boldsymbol{r}_r^\mathsf{T}, \; {}^G\dot{\boldsymbol{r}}_r^\mathsf{T}, \; \boldsymbol{b}_g^\mathsf{T}, \; \boldsymbol{b}_a^\mathsf{T}\right]^\mathsf{T},$$

$$\boldsymbol{x}_{\text{clk},r} \triangleq \left[c\delta t_r, c\dot{\delta t}_r\right]^\mathsf{T}, \quad {}^G\boldsymbol{r}_r \triangleq [x_r, y_r, z_r]^\mathsf{T}$$

${}^I_G\bar{\boldsymbol{q}}^\mathsf{T} \in \mathbb{R}^4$: quaternion vector
$\boldsymbol{b}_g \in \mathbb{R}^3$: gyroscope bias
$\boldsymbol{b}_a \in \mathbb{R}^3$: accelerometer bias

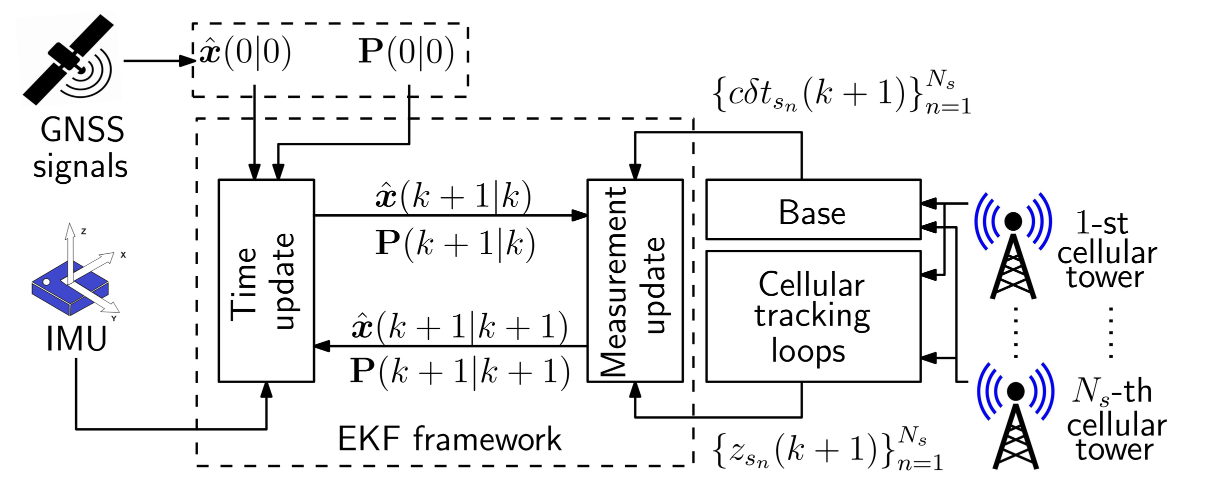
Measurement Model

$$\boldsymbol{z}_s = \left[z_{s_1}, \ldots, z_{s_{N_s}}\right]^\mathsf{T}, \quad \boldsymbol{r}_{s_n} \triangleq [x_{s_n}, y_{s_n}, z_{s_n}]^\mathsf{T},$$

$$z_{s_n}(k) = \left\|{}^G\boldsymbol{r}_r(k) - \boldsymbol{r}_{s_n}\right\|_2 + c\left[\delta t_r(k) - \delta t_{s_n}(k)\right] + v_{s_n}(k)$$

Navigation Framework

The observations $\{z_{s_n}\}_{n=1}^{N_s}$ are fused through an extended Kalman filter (EKF), which produces an estimate of the receiver's state vector $\hat{\boldsymbol{x}}$ and an associated estimation error covariance $\mathbf{P}$.



Outlier Detection

In order to distinguish between outlier-free measurements and those subject to outliers, a measurable scalar parameter is defined that provides information about pseudorange measurement errors. This parameter, called a test statistic, is a random variable with a known distribution (i.e., chi-square) and is defined as

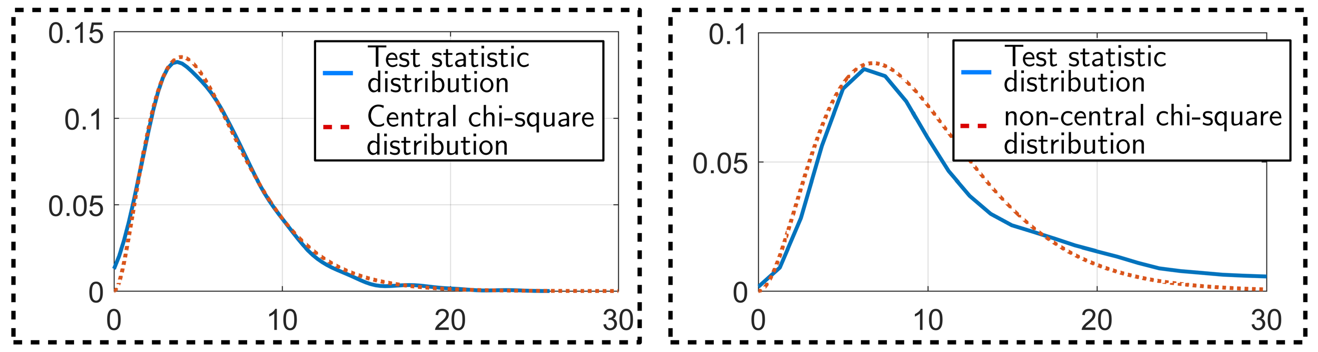
$$\varphi(k+1) \triangleq \boldsymbol{\nu}^\mathsf{T}(k+1)\mathbf{S}^{-1}(k+1)\boldsymbol{\nu}(k+1),$$

where $\boldsymbol{\nu}$ and $\mathbf{S}$ represent the innovation vector and its associated covariance, respectively. Outlier detection is achieved by comparing $\varphi(k+1)$ against a detection threshold T_h, namely

$$\varphi(k+1) \leq T_h : \text{no outliers present,}$$
$$\varphi(k+1) > T_h : \text{outlier present.}$$

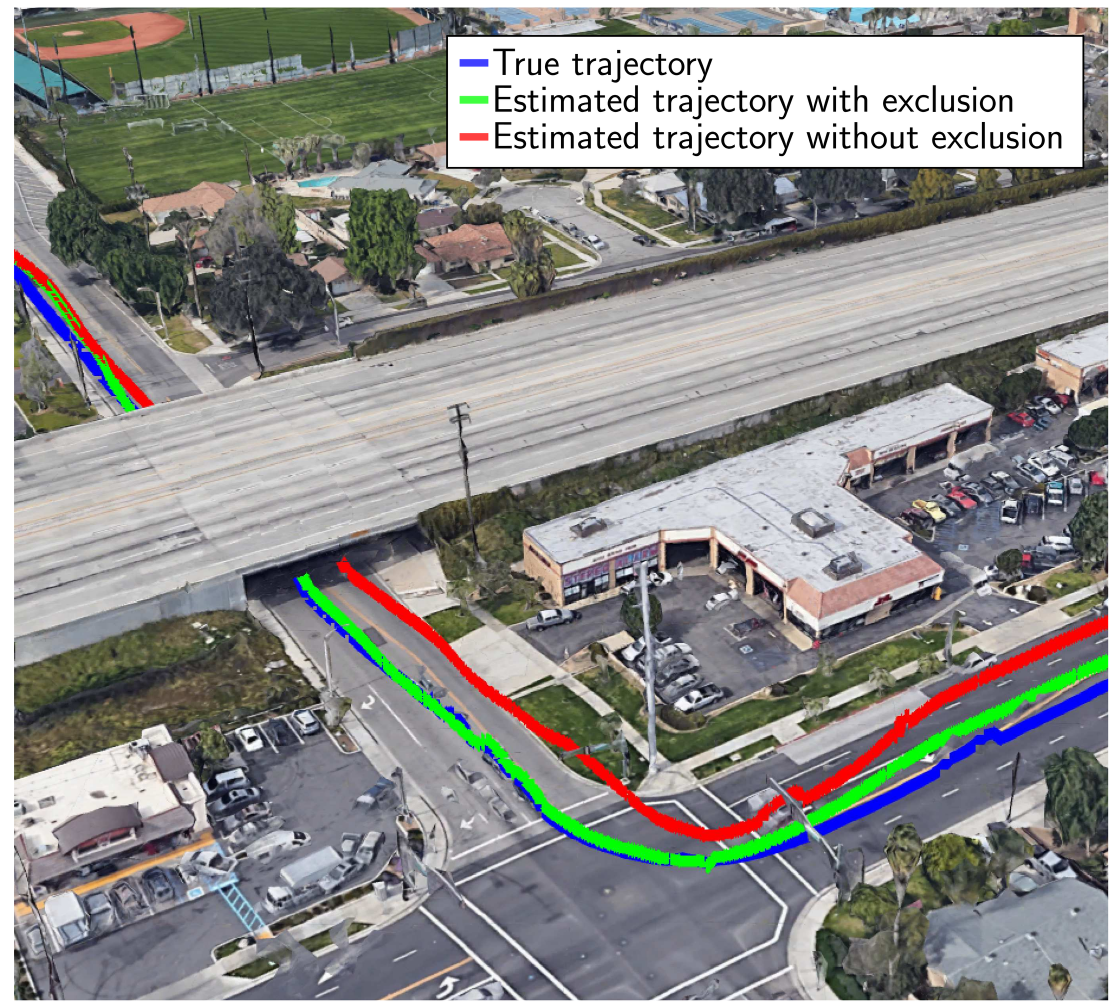
Outlier Exclusion

Step 1: Construct N_s subsets of $N_s - 1$ pseudorange measurements each of which excludes one pseudorange measurement.
Step 2: Assuming that only one of the cellular measurements is outlier, apply outlier detection procedure to each subset.
Step 3: This results in a test statistic failure in all subsets except one.
Step 4: Feed the navigation solution block with the measurement subset with successful test statistic.

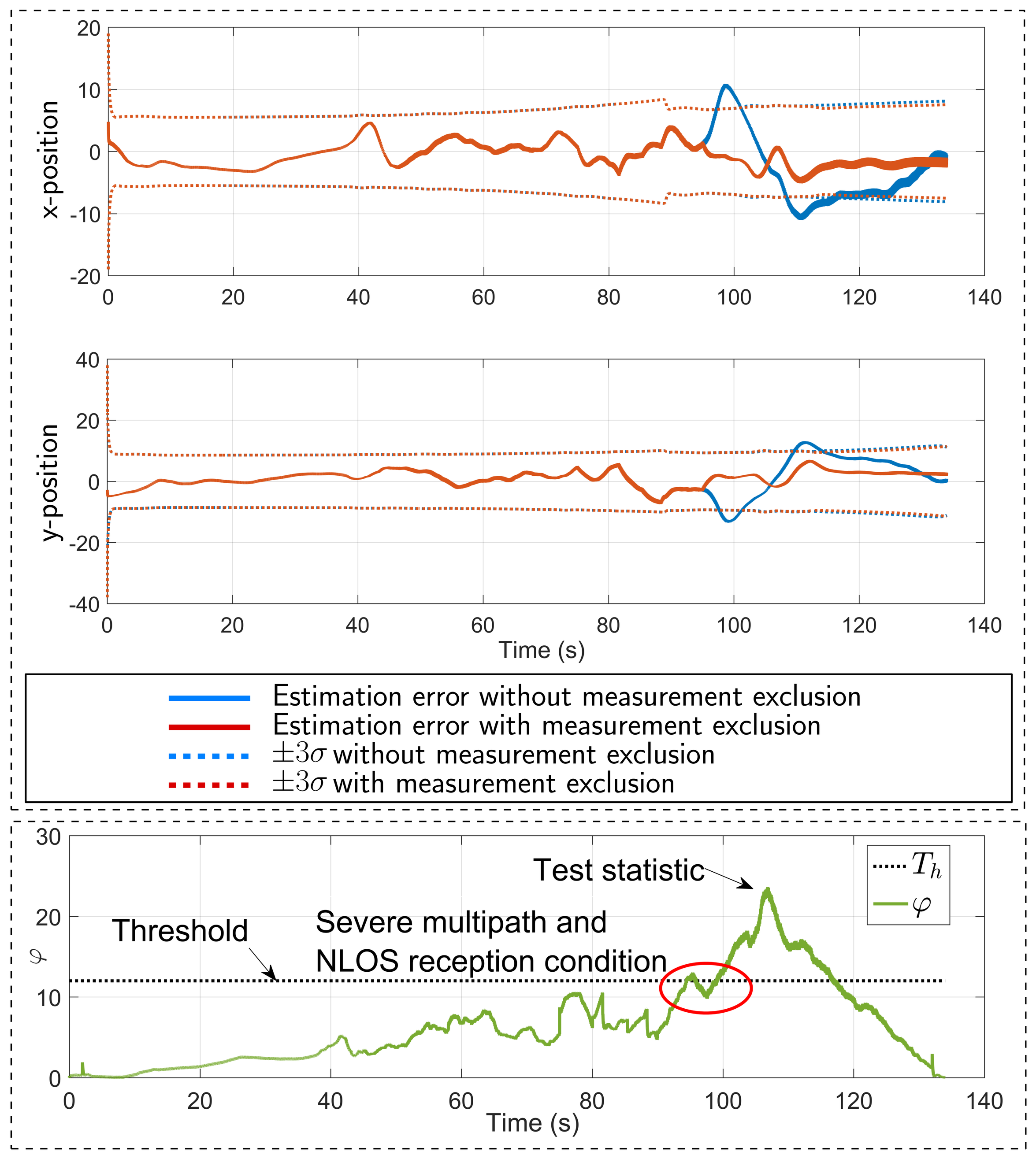


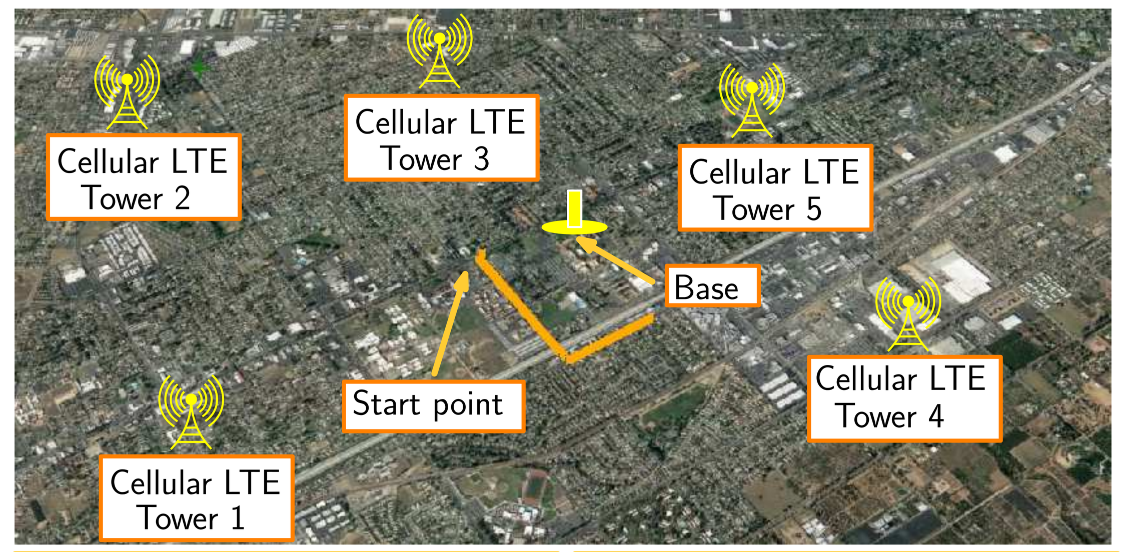
Test statistic PDF in the subset without outlier measurement

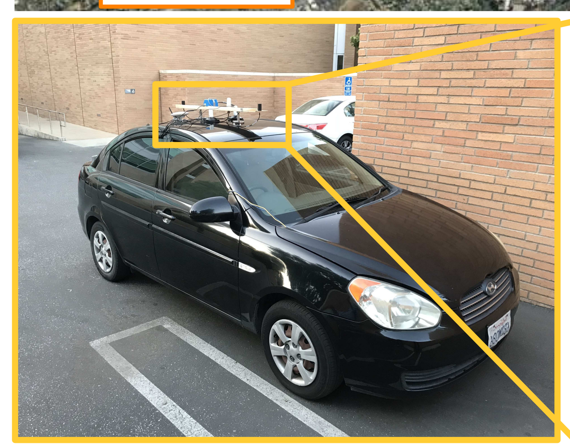
Test statistic PDF in $N_s - 1$ subsets with outlier measurement

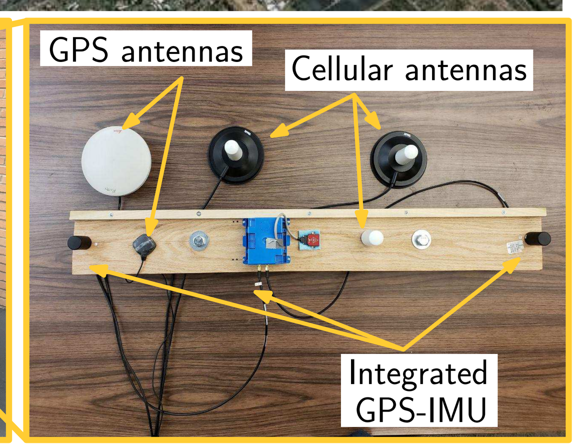


Experimental Demo









Navigation solutions with and without outlier exclusion

Error	With exclusion	Without exclusion	Improvement
RMSE 2-D	4.8 m	8.2 m	42 %
Max. 2-D	11.6 m	20.4 m	43.3 %

Acknowledgment and References

This work was supported in part by the National Science Foundation (NSF) under Grant 1751205 and the Office of Naval Research (ONR) under Grant N00014-16-1-2305 and Grant N00014-16-1-2809.

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