CVPR LONG BEACH CALIFORNIA
June 16-20, 2019

Baidu 百度 | apollo

CVPR 2019 Tutorial

Multi-sensor Fusion Based Localization

Shiyu Song

songshiyu@baidu.com

Principal Architect

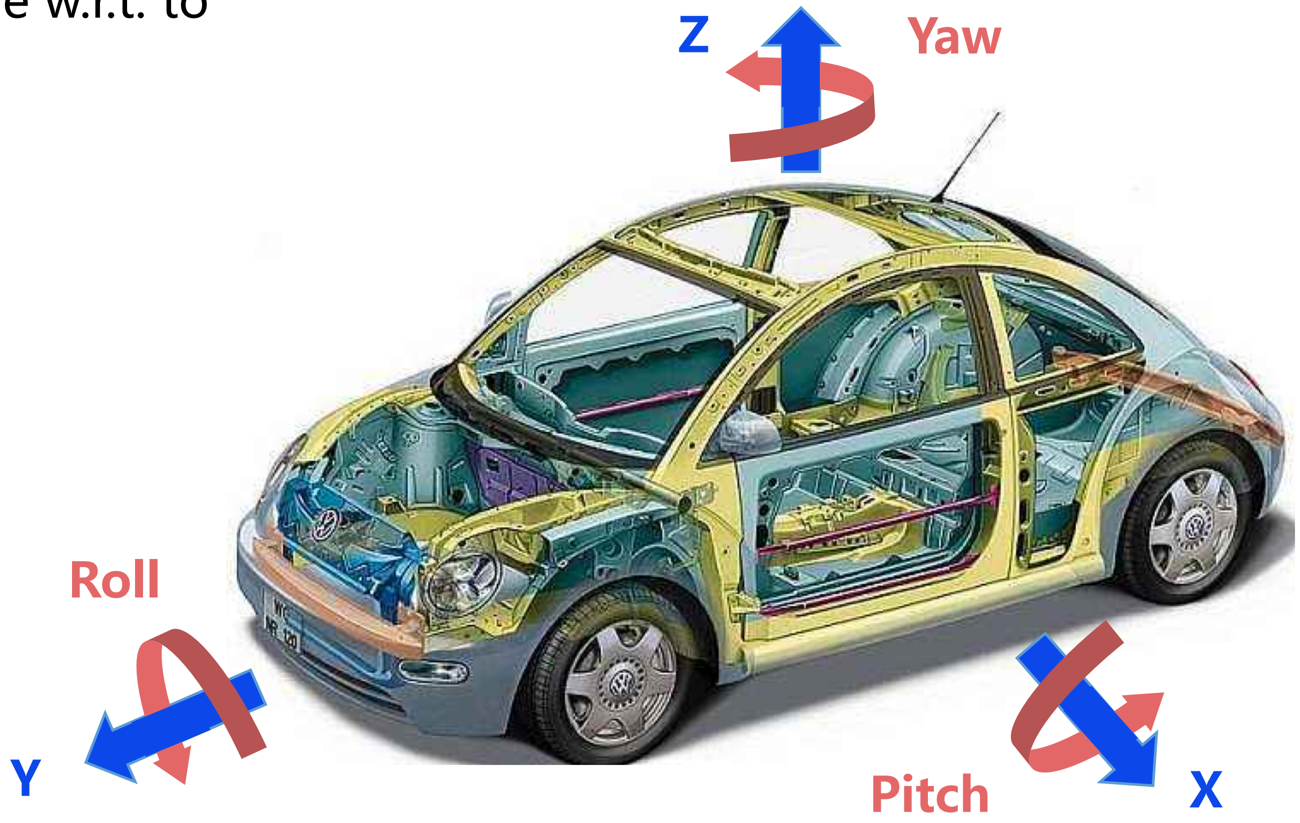
Baidu Autonomous Driving Technology Department (ADT)

Introduction

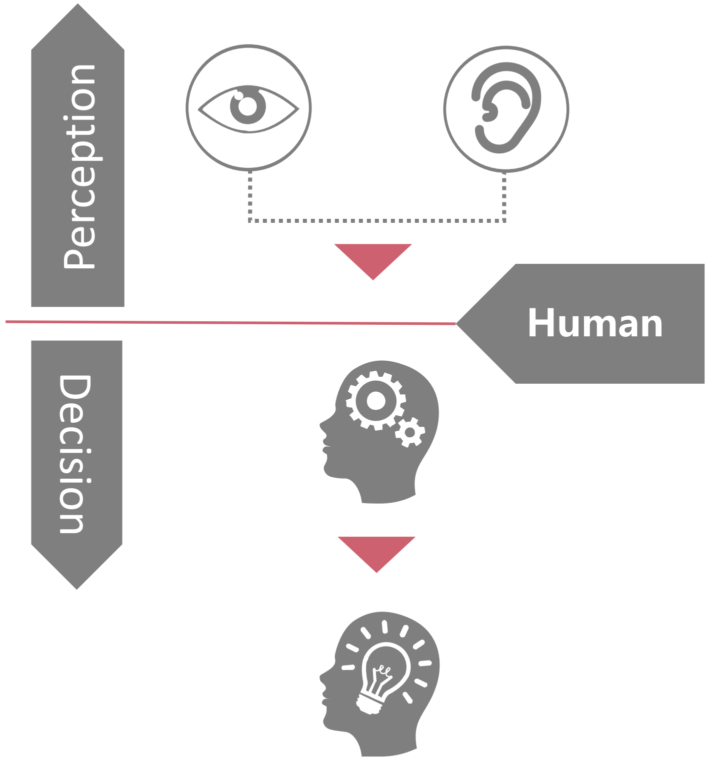
Introduction: Localization System

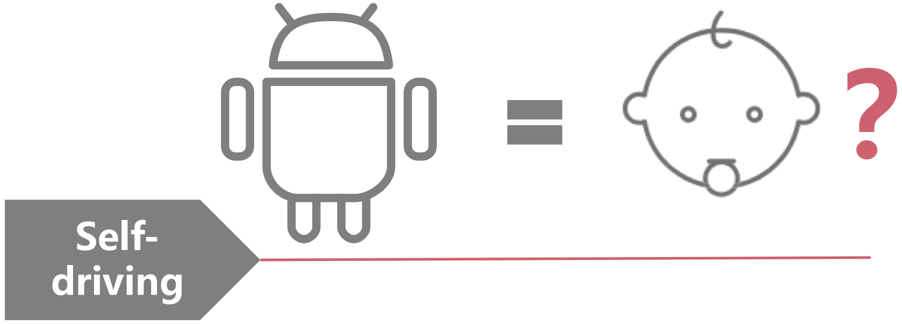
Estimate position and orientation of a vehicle w.r.t. to a coordinate system (e.g., UTM): **6 DOF**

Item	Variable	DOF
Position	X、Y、Z	3
Orientation	Yaw、Pitch、Roll	3
Velocity	v_x、v_y、v_z	3
Acceleration	a_x、a_y、a_z	3
Angular Velocity	ω_x、ω_y、ω_z	3

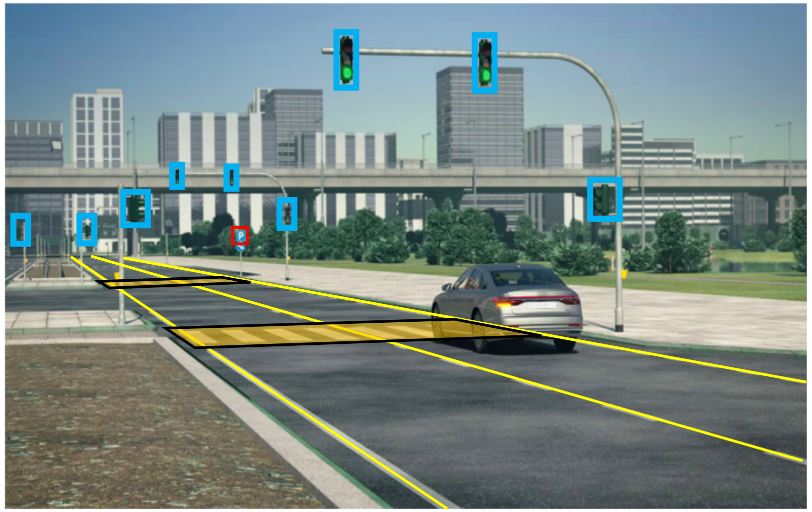


Why we need localization and map?

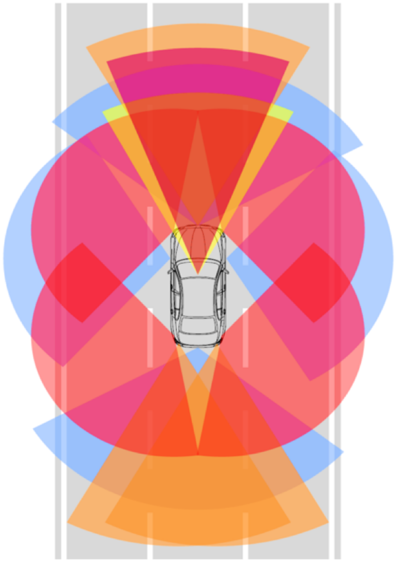




Prior Guidance



Perception Range



SAE Level and Localization

1	2	3	4	5
Mercedes-Benz	TESLA			
Adaptive Cruise Control (ACC) Lane Departure Warning (LDW)	Tesla Autopilot Lane Keeping Assistant (LKA)	"Eyes off" Human interruption in limited time	"Mind off" Self-driving in limited scenarios, safe pull-over	"No steering wheel" Self-driving, robot-taxi
No Map or Localization		Need Map and Localization		

Vision as primary sensor

LiDAR as primary sensor

System Requirement

L4/L5 autonomous driving need a Precise、Reliable、Universal localization module

Precise

Centimeter positioning accuracy and sub-degree orientation accuracy

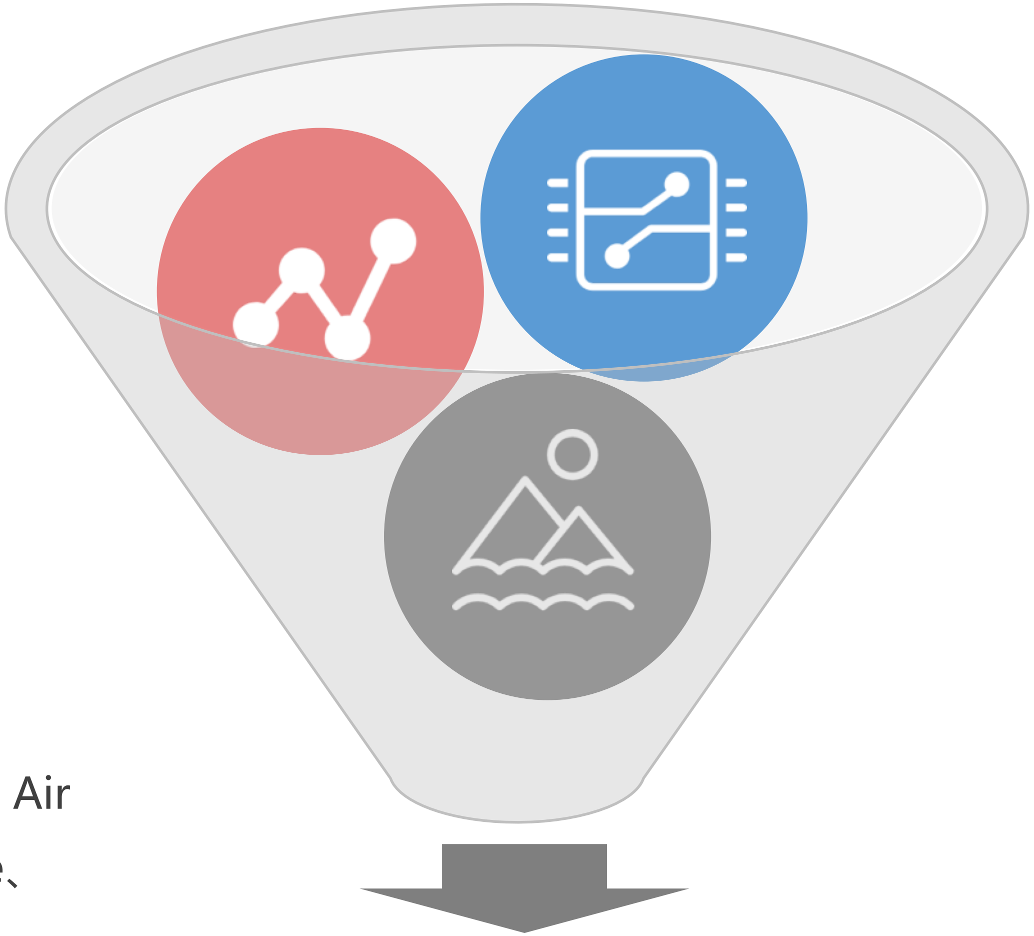
Reliable

Critical dependency, need to be available all the time

Universal

Available in challenging scenarios, such as tree-lined roads, tunnels, downtown. Available in severe weathers, including rainy, snowy, foggy days.

Localization Methods



Signal-based

GNSS、RFID、Cell Phone、Wifi、FM radio、UWB

Dead-Reckoning

IMU、Wheel Odometry

Feature Matching

LiDAR、Radar、Camera

Magnetometer、Air Pressure Gauge、Depth Gauge

Common Localization Methods and Sensors

Global Navigation Satellite System (GNSS)

Solution - Global Navigation Satellite System

Global Navigation Satellite System (GNSS):

GPS (United States), GLONASS (Russia), Beidou (China), Galileo (Europe), QZSS (Japan)

Basic Functions:

Measure position, velocity and precise time (PVT)

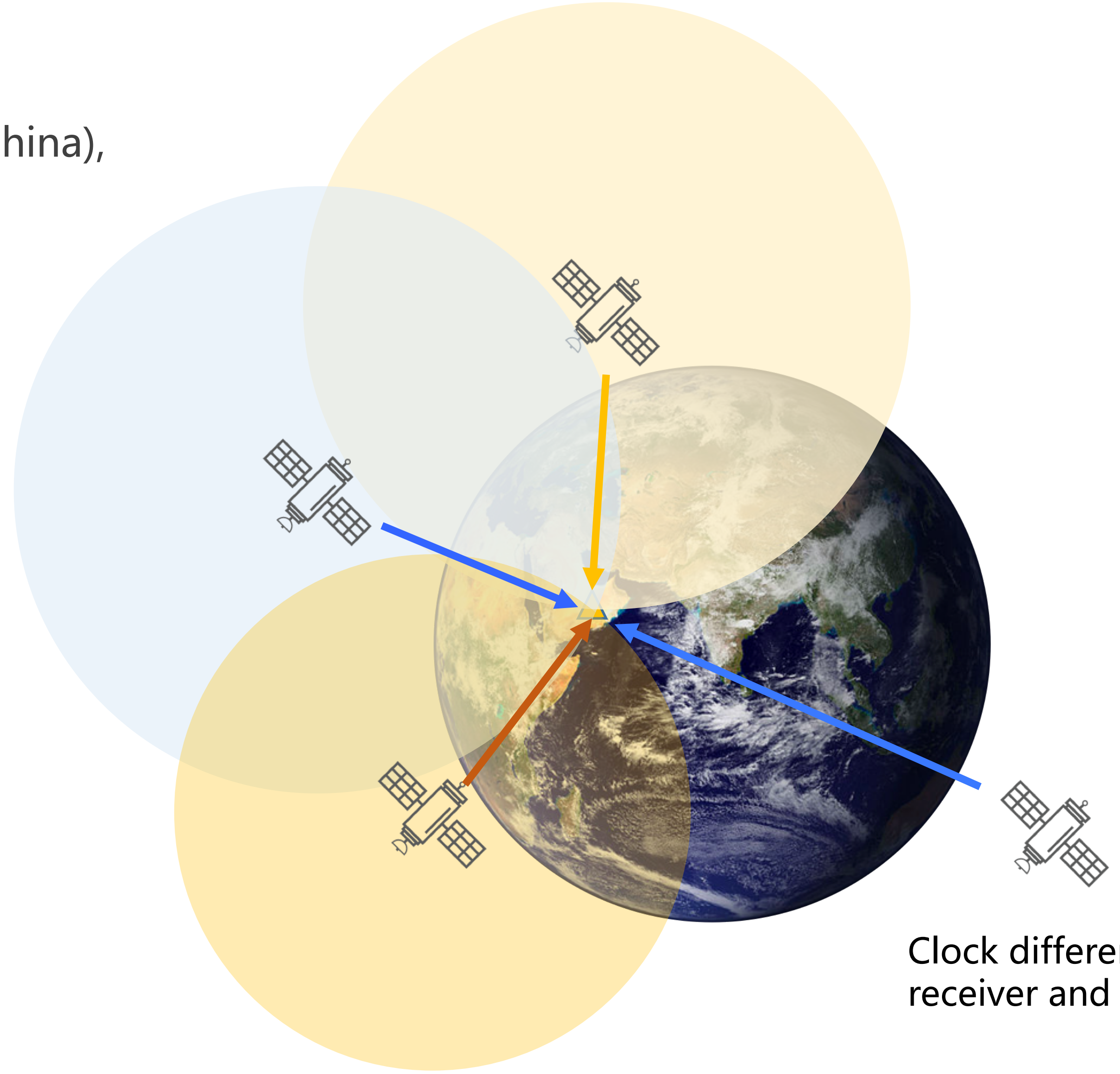
Basic Technical Principle:

Time of arrival (TOA)

Accuracy:

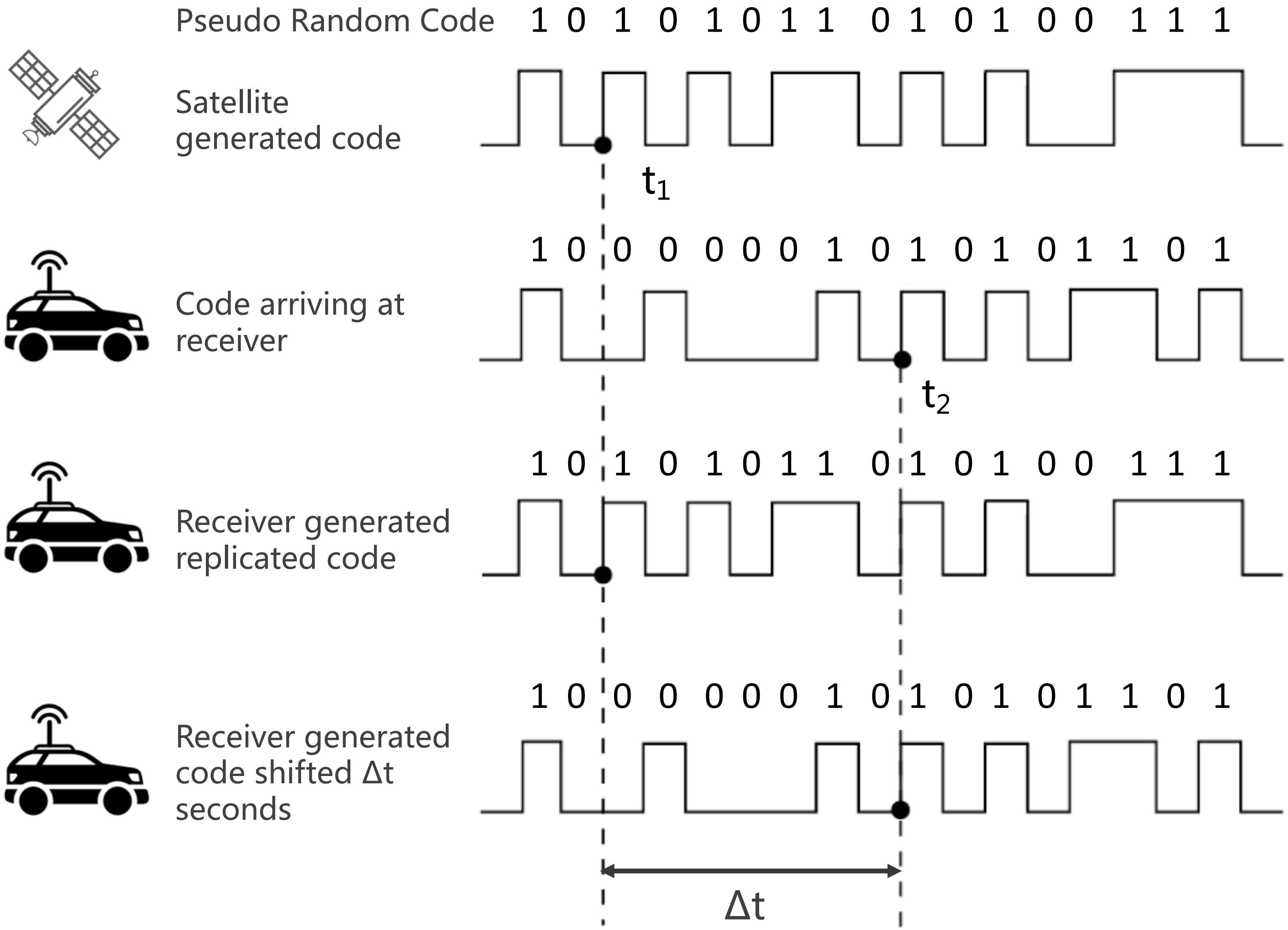
Single Point Positioning: about 5 m (1 sigma)

Real-time Kinematic (RTK): 1cm + 1 ppm (1 sigma)



Clock difference between receiver and satellite

Solution - Global Navigation Satellite System



Single Point Positioning

Accuracy: about 5 m

Range = Δt * c,

where c is the speed of light

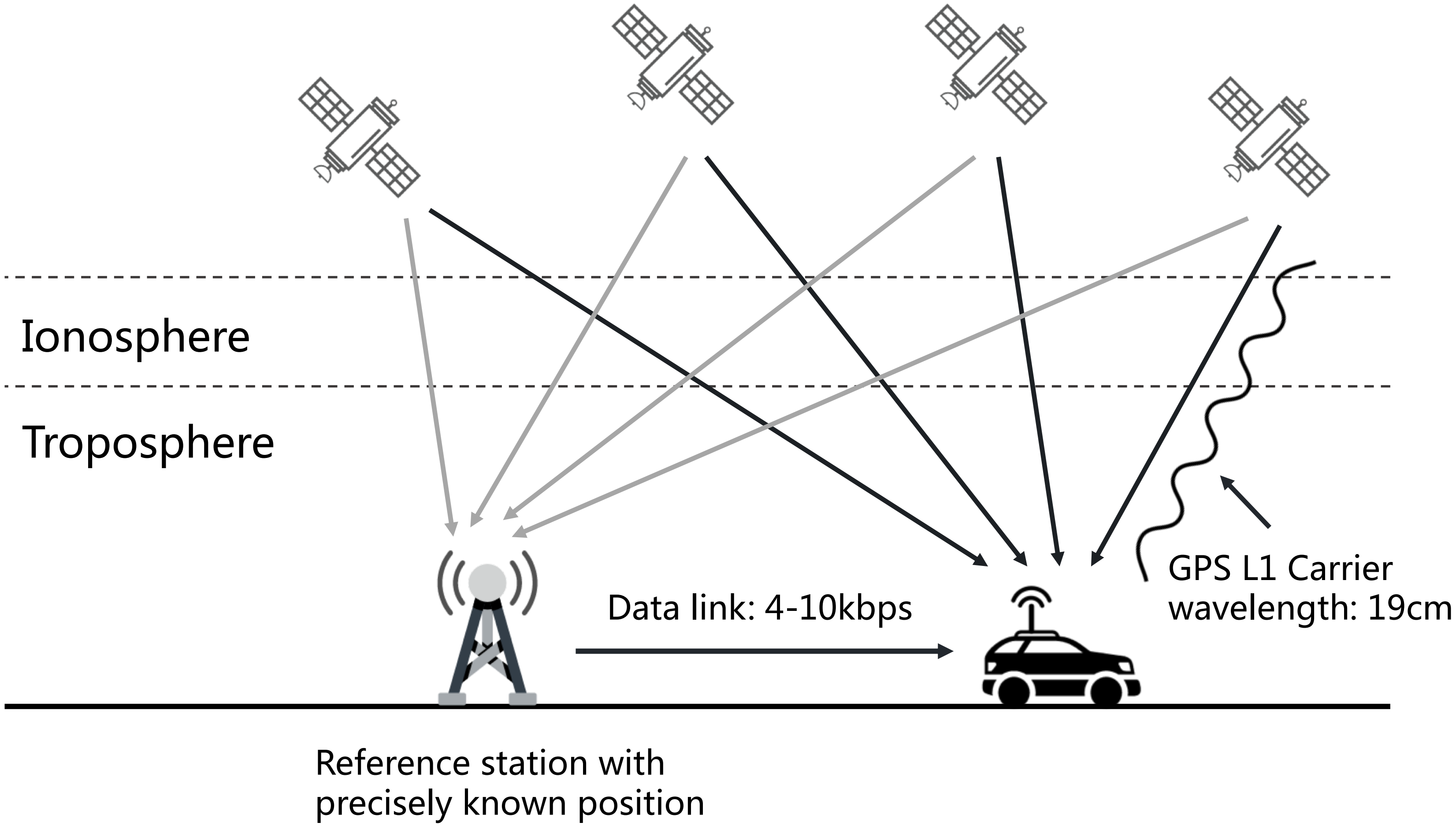
Solution - Global Navigation Satellite System

Real-time Kinematic (RTK)

Accuracy: 1cm + 1ppm

Core Technique:

- Carrier-phase tracking
- Differential GNSS

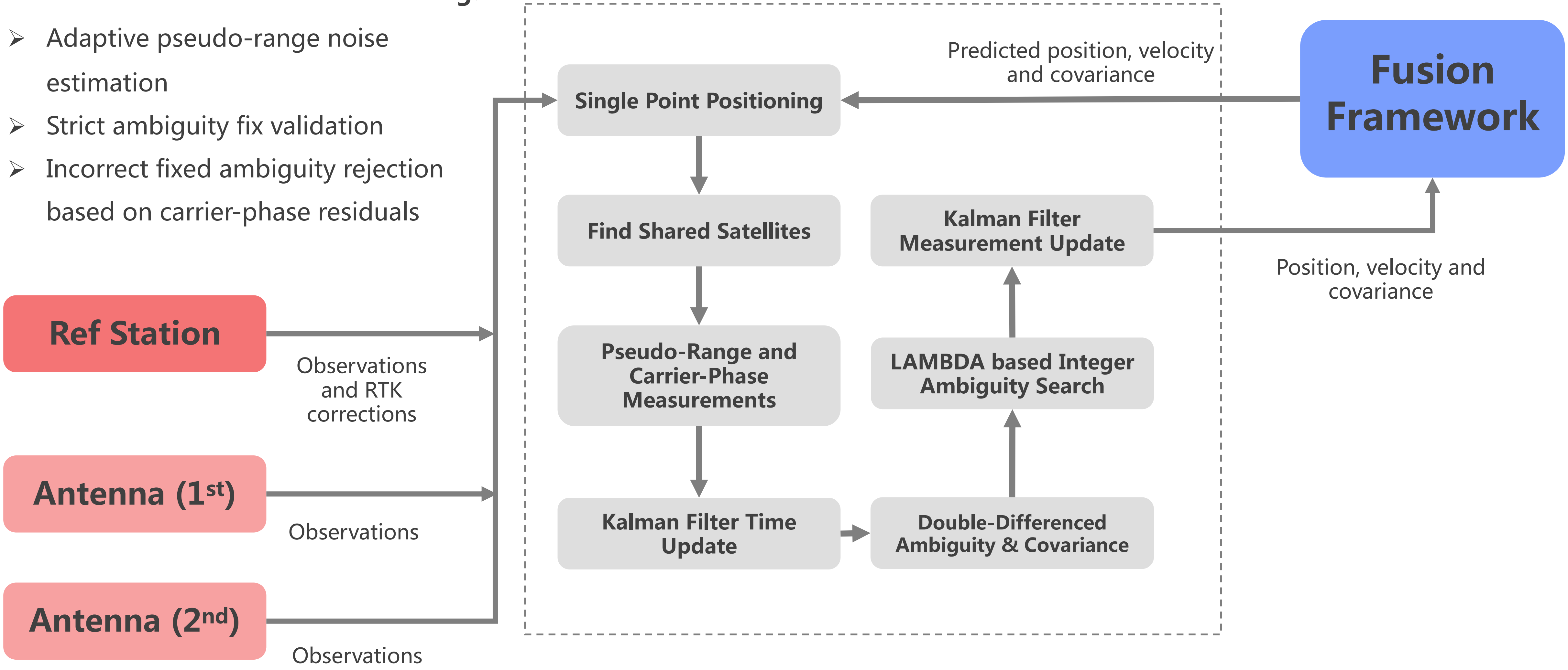


SPP Error Sources (m)		
✓	Ephemeris	~1.4
✓	Satellite Clock	~1.4
✓	Ionosphere	~2
✓	Troposphere	~0.5
✓	Pseudorange noise	~0.5
✗	Multipath	~1.0

Solution - Global Navigation Satellite System

Better Robustness and Error Modeling:

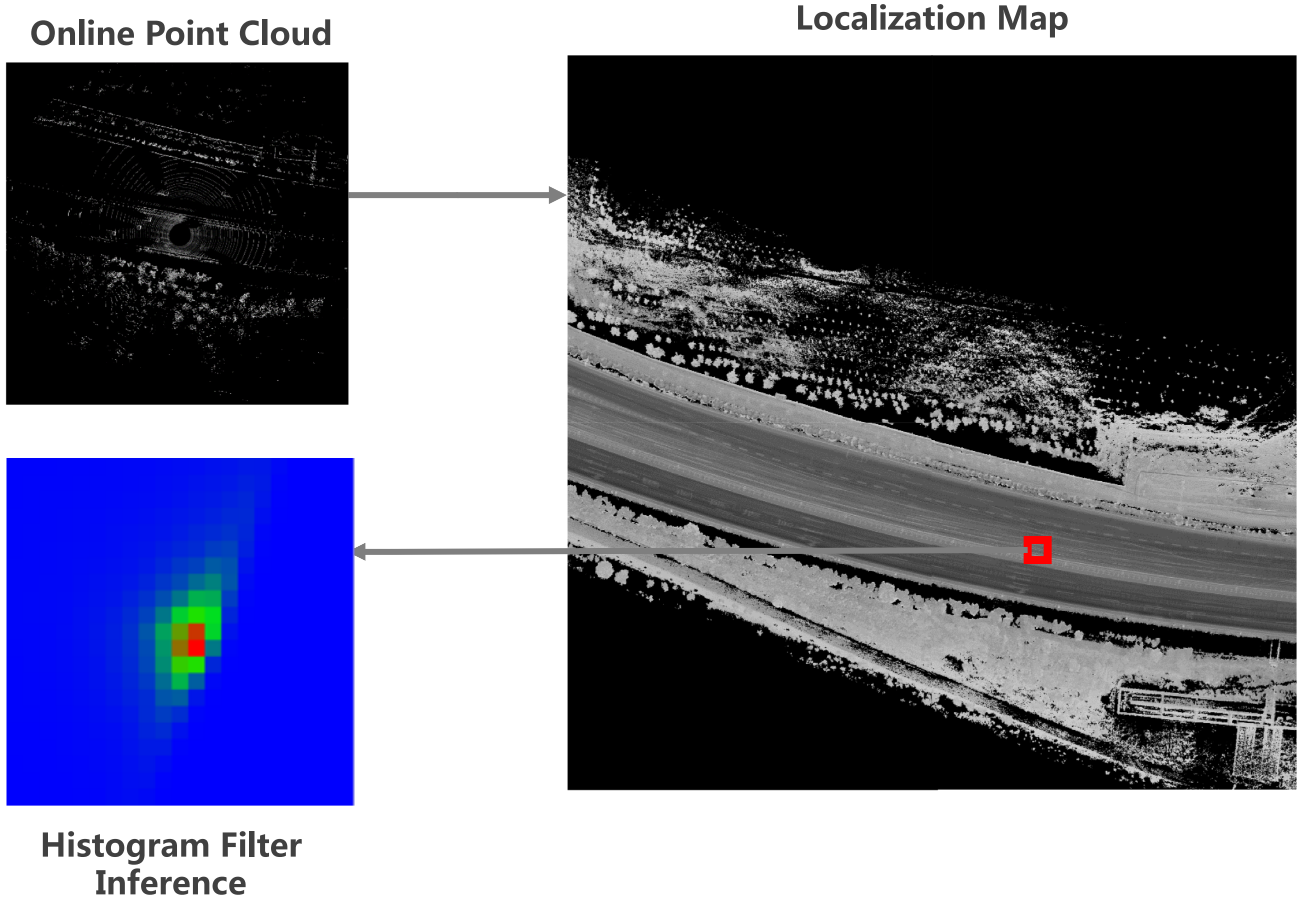
- Adaptive pseudo-range noise estimation
- Strict ambiguity fix validation
- Incorrect fixed ambiguity rejection based on carrier-phase residuals



G. Wan, X. Yang, R. Cai, H. Li, Y. Zhou, H. Wang, S. Song, Robust and Precise Vehicle Localization based on Multi-sensor Fusion in Diverse City Scenes, ICRA 2018

LiDAR Localization

Solution – LiDAR Localization



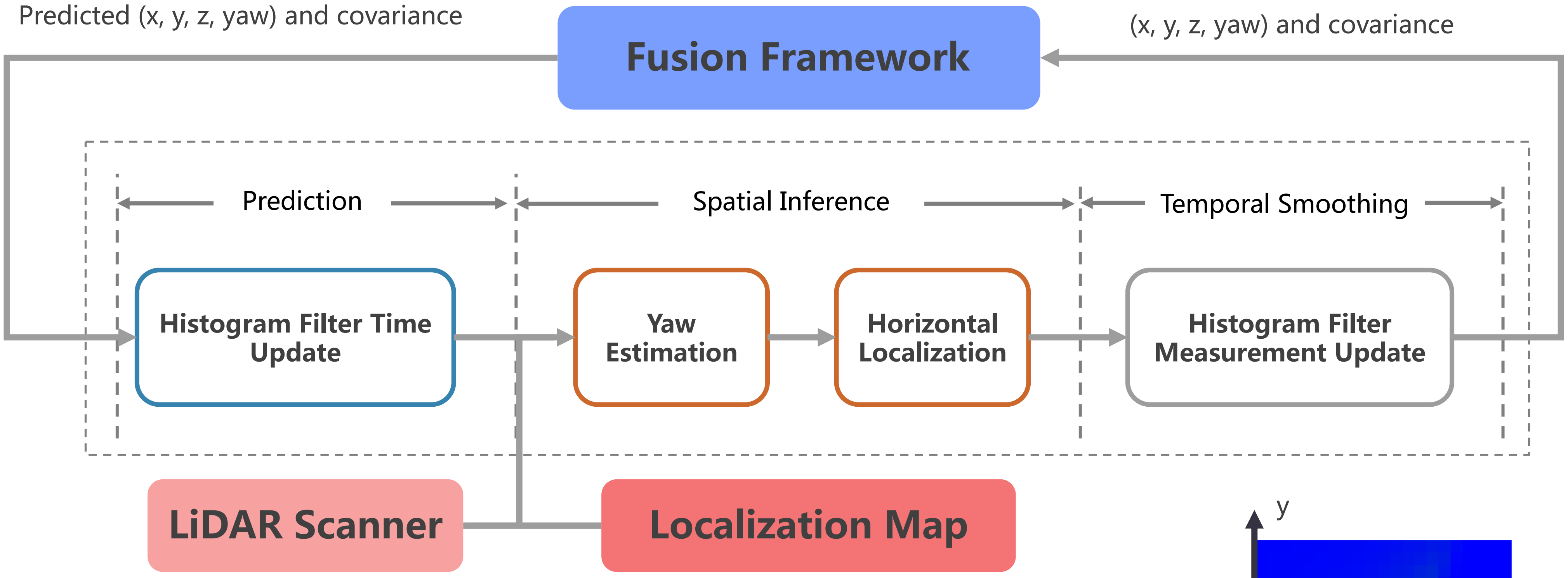
Advantage

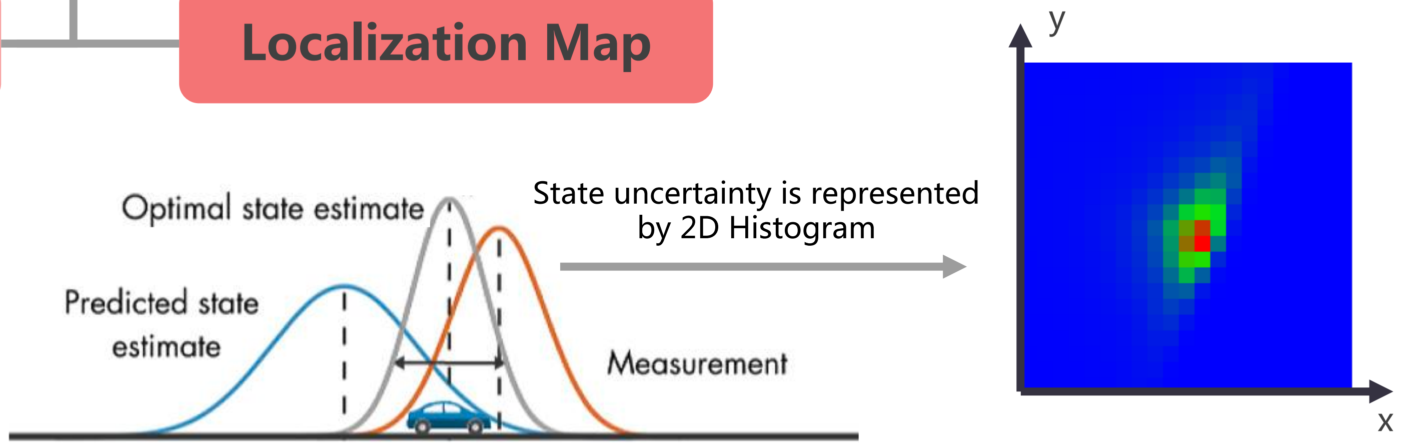
- Precise and accurate
- No external dependences

Disadvantage

- Pre-collected map required
- Map update required
- Suffer in server weather, such as snow.

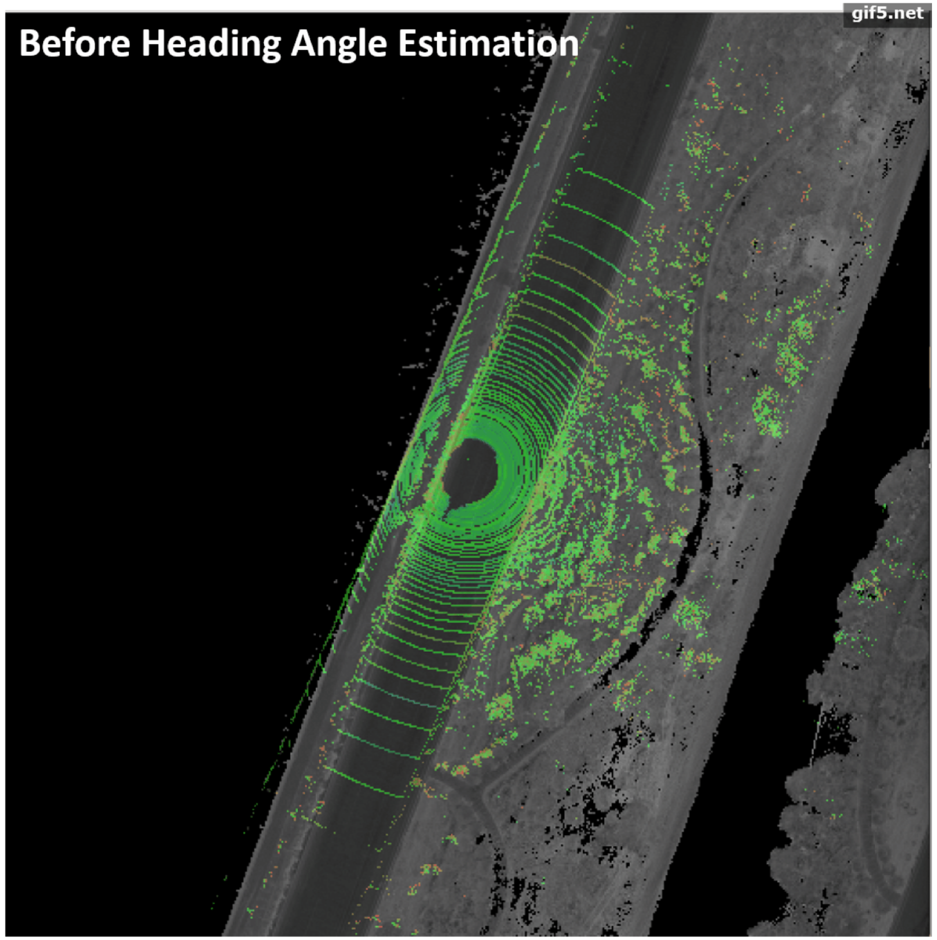
Solution – LiDAR Localization



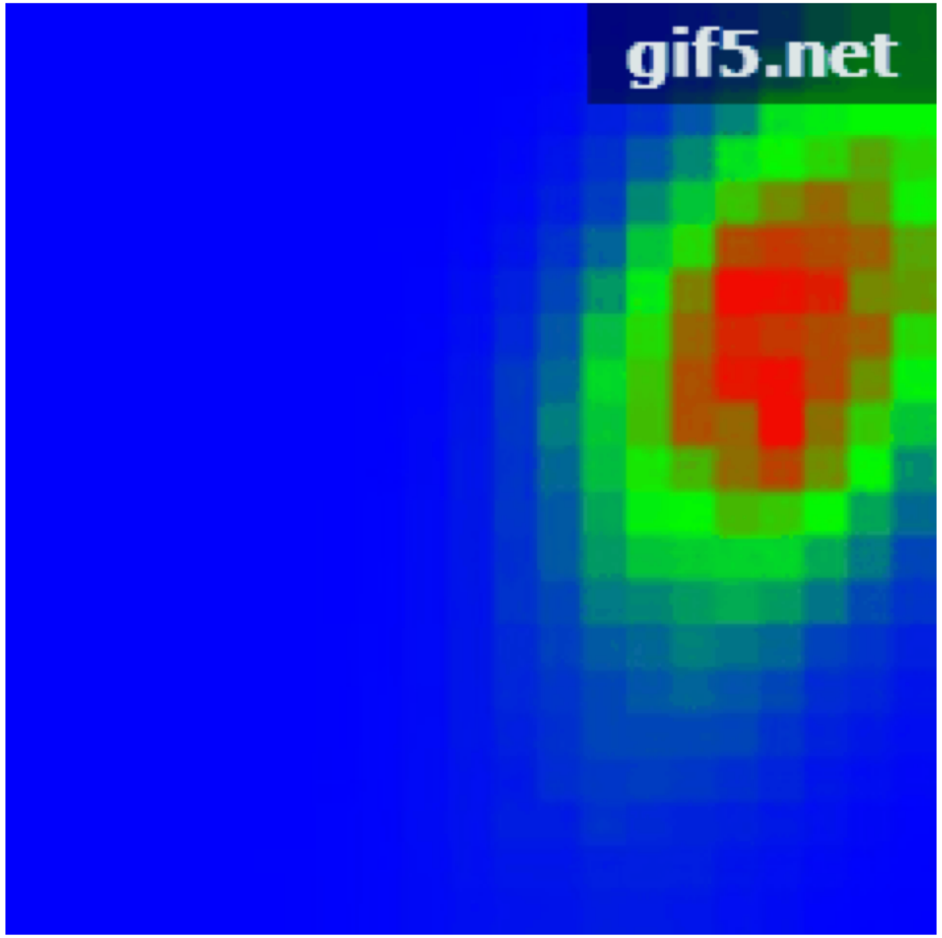


G. Wan, X. Yang, R. Cai, H. Li, Y. Zhou, H. Wang, S. Song, Robust and Precise Vehicle Localization based on Multi-sensor Fusion in Diverse City Scenes, ICRA 2018

Solution – LiDAR Localization



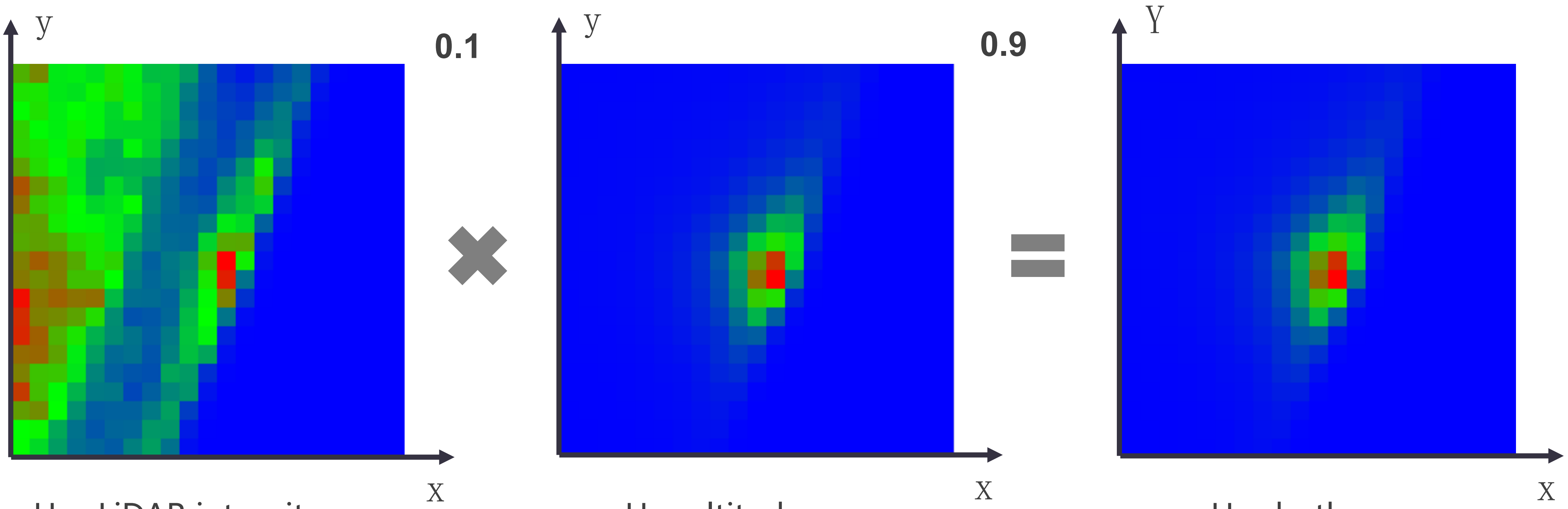
1.5o error in heading estimation



Horizontal Localization
(with or without heading estimation)

G. Wan, X. Yang, R. Cai, H. Li, Y. Zhou, H. Wang, S. Song, Robust and Precise Vehicle Localization based on Multi-sensor Fusion in Diverse City Scenes, ICRA 2018

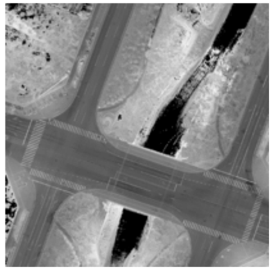
Solution – LiDAR Localization

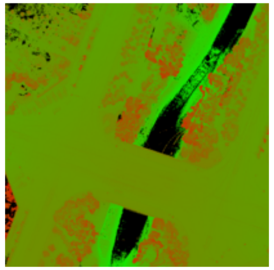


Use LiDAR intensity cue

Use altitude cue

Use both cues

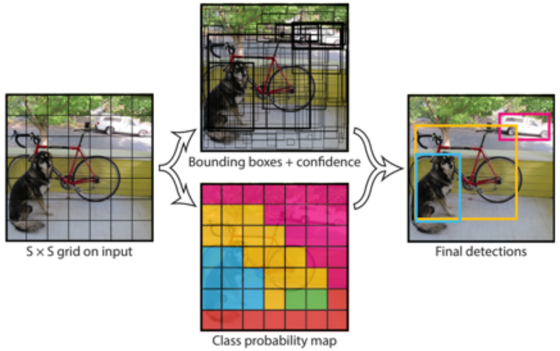




G. Wan, X. Yang, R. Cai, H. Li, Y. Zhou, H. Wang, S. Song, Robust and Precise Vehicle Localization based on Multi-sensor Fusion in Diverse City Scenes, ICRA 2018

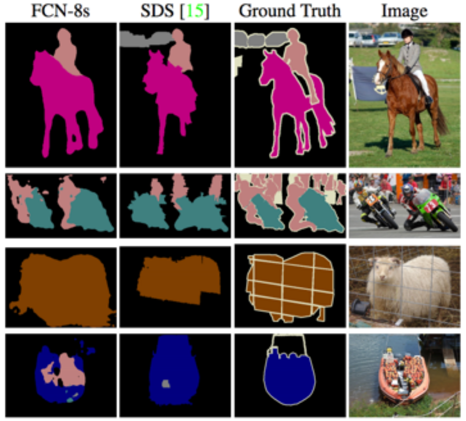
Learning-based Methods

Object Detection



J. Redmon, et al., CVPR 2016

Semantic Segmentation



J. Long, et al., CVPR 2015

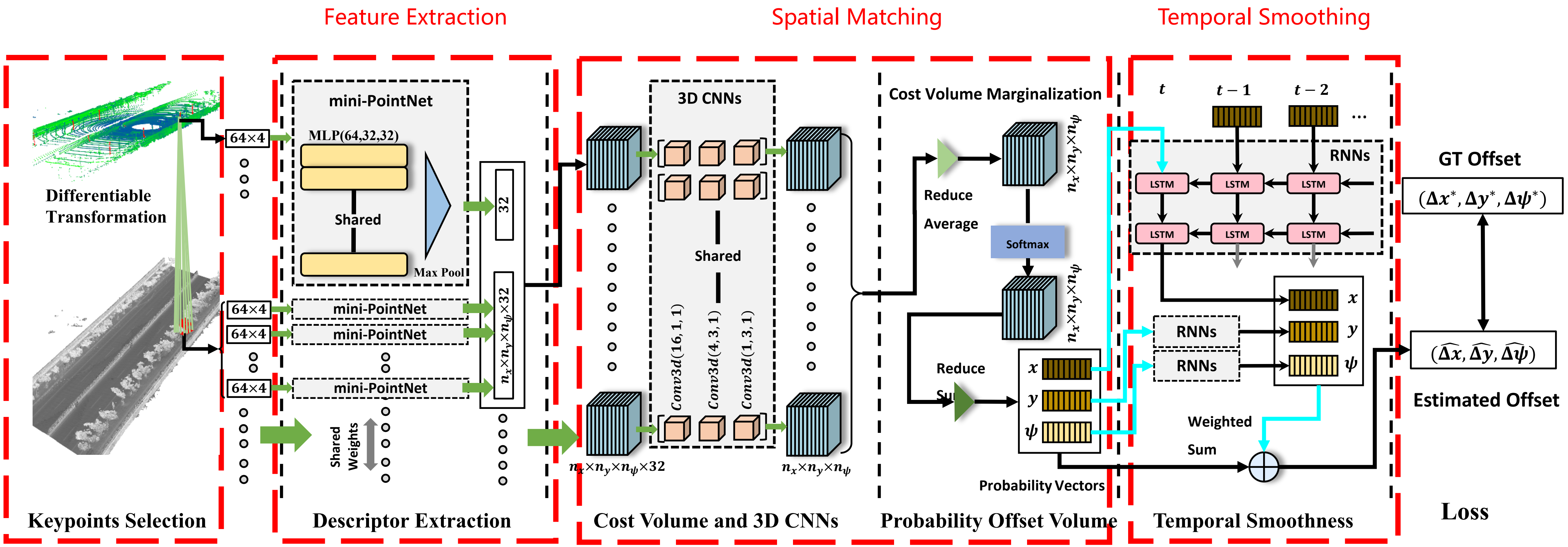
Image Classification

A. Krizhevsky, et al., NIPS 2012

Geometric Problem

?

Learning-based LiDAR Localization



W. Lu, Y. Zhou, G. Wan, S. Hou, S. Song, L3-Net: Towards Learning based LiDAR Localization for Autonomous Driving, CVPR 2019

Learning-based LiDAR Localization

DataSet	Methods	Horiz. RMS	Horiz. Max	Long. RMS	Lat. RMS	< 0.1m Pct.	< 0.2m Pct.	< 0.3m Pct.	Yaw. RMS	Yaw. Max	$< 0.1°$ Pct.	$< 0.3°$ Pct.	$< 0.6°$ Pct.
BaylandsToSeafood	Levinson et al.[18]	0.148	1.501	0.115	0.074	54.62%	82.41%	91.10%	-	-	-	-	-
	Wan et al.[29]	**0.036**	**0.203**	**0.026**	**0.019**	**98.88%**	**99.98%**	100.0%	0.054	0.372	86.82%	99.86%	100.0%
	Ours.(WithoutRNN)	0.054	0.328	0.041	0.026	94.49%	99.77%	99.95%	0.029	0.294	98.56%	100.0%	100.0%
	Ours.(WithRNN)	0.050	0.209	0.039	0.024	96.48%	99.89%	100.0%	**0.020**	**0.179**	**99.35%**	100.0%	100.0%
ColumbiaPark	Levinson et al.[18]	0.063	0.202	0.045	0.034	87.30%	99.99%	100.0%	-	-	-	-	-
	Wan et al.[29]	0.046	0.160	0.034	0.024	96.46%	100.0%	100.0%	0.081	0.384	67.27%	99.74%	100.0%
	Ours.(WithoutRNN)	0.047	0.161	0.034	0.025	95.82%	100.0%	100.0%	0.049	0.322	92.57%	99.99%	100.0%
	Ours.(WithRNN)	**0.043**	**0.159**	**0.032**	**0.023**	**98.02%**	100.0%	100.0%	**0.028**	**0.190**	**99.50%**	**100.0%**	100.0%
Highway237	Levinson et al.[18]	0.161	0.622	0.138	0.061	37.05%	69.90%	86.09%	-	-	-	-	-
	Wan et al.[29]	0.049	0.196	0.038	0.022	93.27%	100.0%	100.0%	0.069	0.302	78.12%	99.94%	100.0%
	Ours.(WithoutRNN)	0.053	0.257	0.046	**0.019**	92.05%	99.77%	100.0%	0.048	0.211	94.51%	100.0%	100.0%
	Ours.(WithRNN)	**0.045**	**0.190**	**0.034**	0.023	**99.01%**	100.0%	100.0%	**0.038**	**0.112**	**99.30%**	100.0%	100.0%
MathildaAVE	Levinson et al.[18]	0.106	0.779	0.086	0.044	65.20%	90.43%	94.83%	-	-	-	-	-
	Wan et al.[29]	**0.040**	0.179	**0.030**	**0.020**	98.72%	100.0%	100.0%	0.060	0.453	82.91%	99.74%	100.0%
	Ours.(WithoutRNN)	0.054	0.379	0.040	0.028	96.82%	99.91%	99.99%	0.033	0.674	97.56%	99.83%	99.97%
	Ours.(WithRNN)	0.051	**0.154**	0.040	0.025	**98.87%**	100.0%	100.0%	**0.019**	**0.176**	**99.31%**	**100.0%**	100.0%
SanJoseDowntown	Levinson et al.[18]	0.103	0.586	0.075	0.055	58.20%	88.39%	97.75%	-	-	-	-	-
	Wan et al.[29]	0.058	0.290	0.039	0.034	87.72%	**99.55%**	100.0%	0.052	0.246	87.82%	100.0%	100.0%
	Ours.(WithoutRNN)	0.057	**0.288**	0.037	0.037	89.81%	98.93%	100.0%	**0.033**	0.274	**99.02%**	100.0%	100.0%
	Ours.(WithRNN)	**0.055**	0.294	**0.036**	0.034	**91.32%**	99.20%	100.0%	0.034	**0.221**	98.86%	100.0%	100.0%
SunnyvaleBigLoop	Levinson et al.[18]	0.132	1.423	0.097	0.070	43.95%	87.51%	94.99%	-	-	-	-	-
	Wan et al.[29]	0.069	0.368	0.050	0.038	80.86%	99.08%	**99.96%**	0.081	0.679	69.51%	98.60%	100.0%
	Ours.(WithoutRNN)	0.060	0.451	0.039	0.037	88.24%	98.99%	99.85%	0.046	0.405	91.32%	99.98%	100.0%
	Ours.(WithRNN)	**0.055**	**0.347**	**0.037**	**0.032**	**92.42%**	**99.14%**	99.94%	**0.033**	**0.262**	**96.44%**	**100.0%**	100.0%

W. Lu, Y. Zhou, G. Wan, S. Hou, S. Song, L3-Net: Towards Learning based LiDAR Localization for Autonomous Driving, CVPR 2019

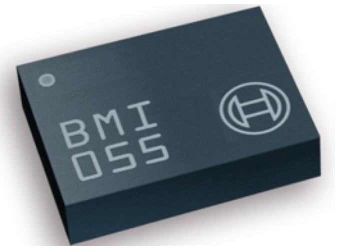
CVPR 2019: L3-Net: Towards Learning based LiDAR Localization for Autonomous Driving
Demo Video: https://www.youtube.com/watch?v=dptbd4D78Mk

Inertial Navigation System (INS)

Solution – Inertial Navigation System (INS)

Fiber Optic Gyros

Precise but pricy



Consumer IMU

Inaccurate but affordable

Advantage

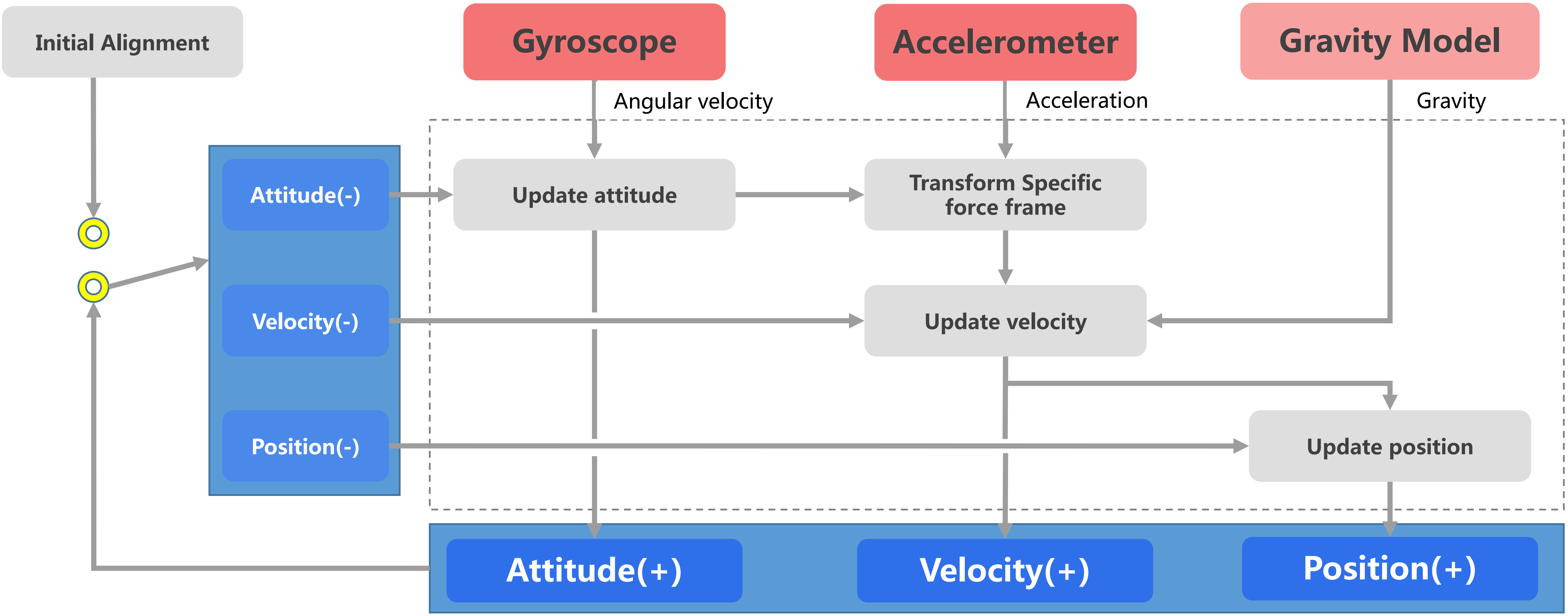
- No external dependences
- High frequency

Disadvantage

- Accumulated error
- Initial alignment required

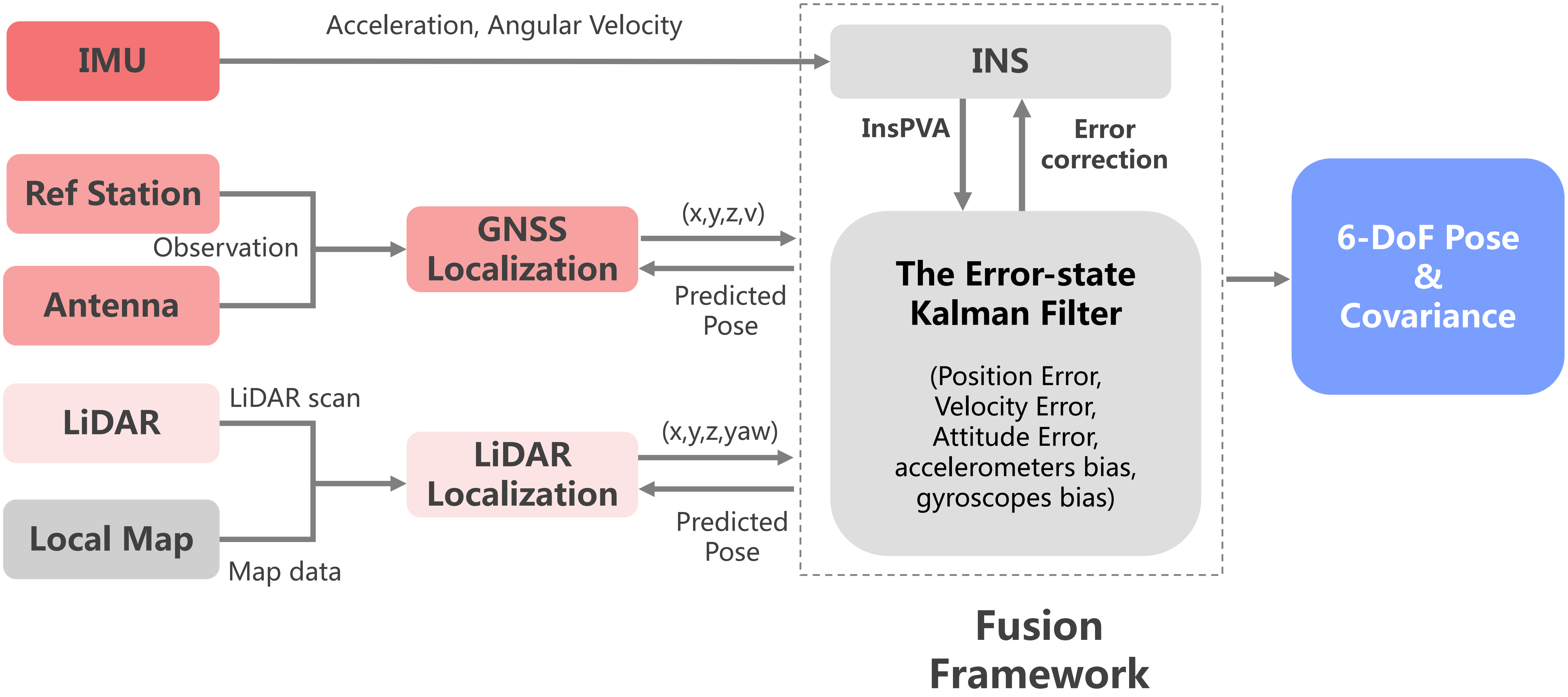
	Price	Accel-meter Bias	Gyroscope Bias	Horizontal Position Error			
Grade	**$**	**[mg]**	**[deg/h]**	**1s**	**10s**	**60s**	**1hr**
Marine	Millions	0.01	0.001	0.005cm	0.5cm	18cm	<50m
Aviation	Hundred thousands	0.03-0.1	0.01	0.017cm	0.17cm	60cm	<1.5km
Intermediate	Ten thousands	0.1-1	0.1	0.05cm	5cm	1m	--
Tactical	Thousands	1-10	1-100	3cm	25cm	--	--
Automotive	Ones	>10	>100	5cm	5m	--	--

Solution – Inertial Navigation System (INS)



Multi-sensor Fusion

Multi-sensor Fusion based Localization



G. Wan, X. Yang, R. Cai, H. Li, Y. Zhou, H. Wang, S. Song, Robust and Precise Vehicle Localization based on Multi-sensor Fusion in Diverse City Scenes, ICRA 2018

ICRA 2018 | Robust and Precise Vehicle Localization based on Multi-sensor Fusion in Diverse City Scenes
Demo Video: https://www.youtube.com/watch?v=8wRs_TaAfUk

Resources

Open Platform and Papers, Books

www.github.com/apolloauto

- Robust and Precise Vehicle Localization based on Multi-sensor Fusion in Diverse City Scenes, ICRA, 2018.
- L3-Net: Towards Learning based LiDAR Localization for Autonomous Driving, CVPR, 2019.

Books

- S. Thrun, W. Burgard, D. Fox, Probabilistic Robotics
- T. Barfoot, State Estimation for Robotics
- P. D. Groves, Principles of GNSS, Inertial, and Multisensor Integrated Navigation Systems

Inside Apollo: Test Scripts

- How to build a localization map using demo data at Apollo Data Open Platform (http://data.apollo.auto)

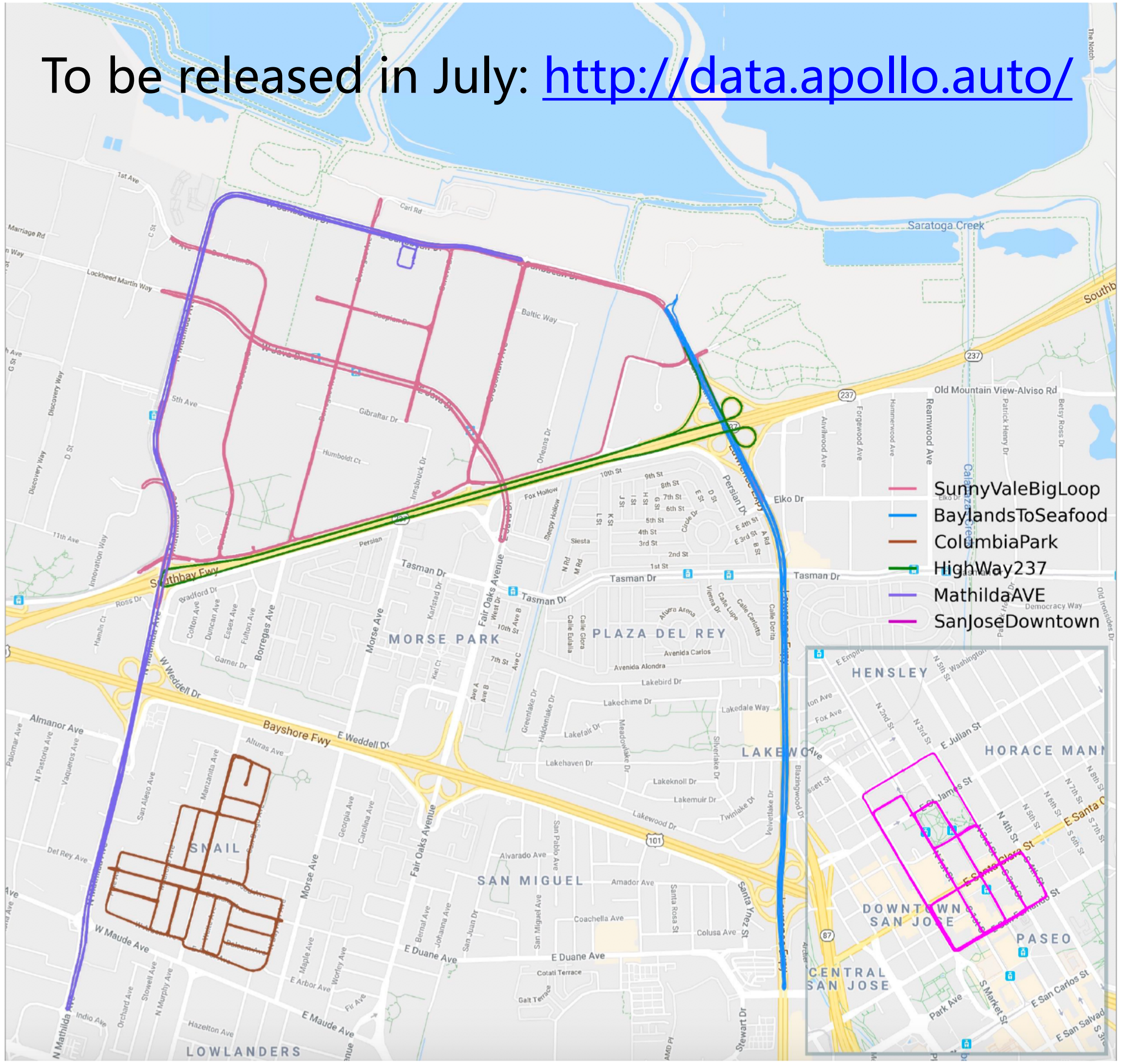
  https://github.com/ApolloAuto/apollo/blob/master/docs/howto/how_to_generate_local_map_for_MSF_localization_module.md

- How to run MSF localization module using demo data at Apollo Data Open Platform (http://data.apollo.auto)

  https://github.com/ApolloAuto/apollo/blob/master/docs/howto/how_to_run_MSF_localization_module_on_your_local_computer.md

Localization Dataset: Apollo-SouthBay

Datasets	Length	Ground Truth	360º LiDAR	Multiple Trials
Ford Campus	5.1km	✓	✓	✗
KITTI	39.2km	✓	✓	✗
Oxford RobotCar	1000.0km	✓	✗	✓
Apollo-SouthBay	380.5km	✓	✓	✓



Sensors:

- Velodyne HDL-64E LiDAR
- NovAtel ProPak 6 and IMU-ISA-100C
- 1080P 15Hz Camera Images.


Thank You !