Integrity Monitoring for Automotive Positioning using GNSS/IMU/Odometer Sensors

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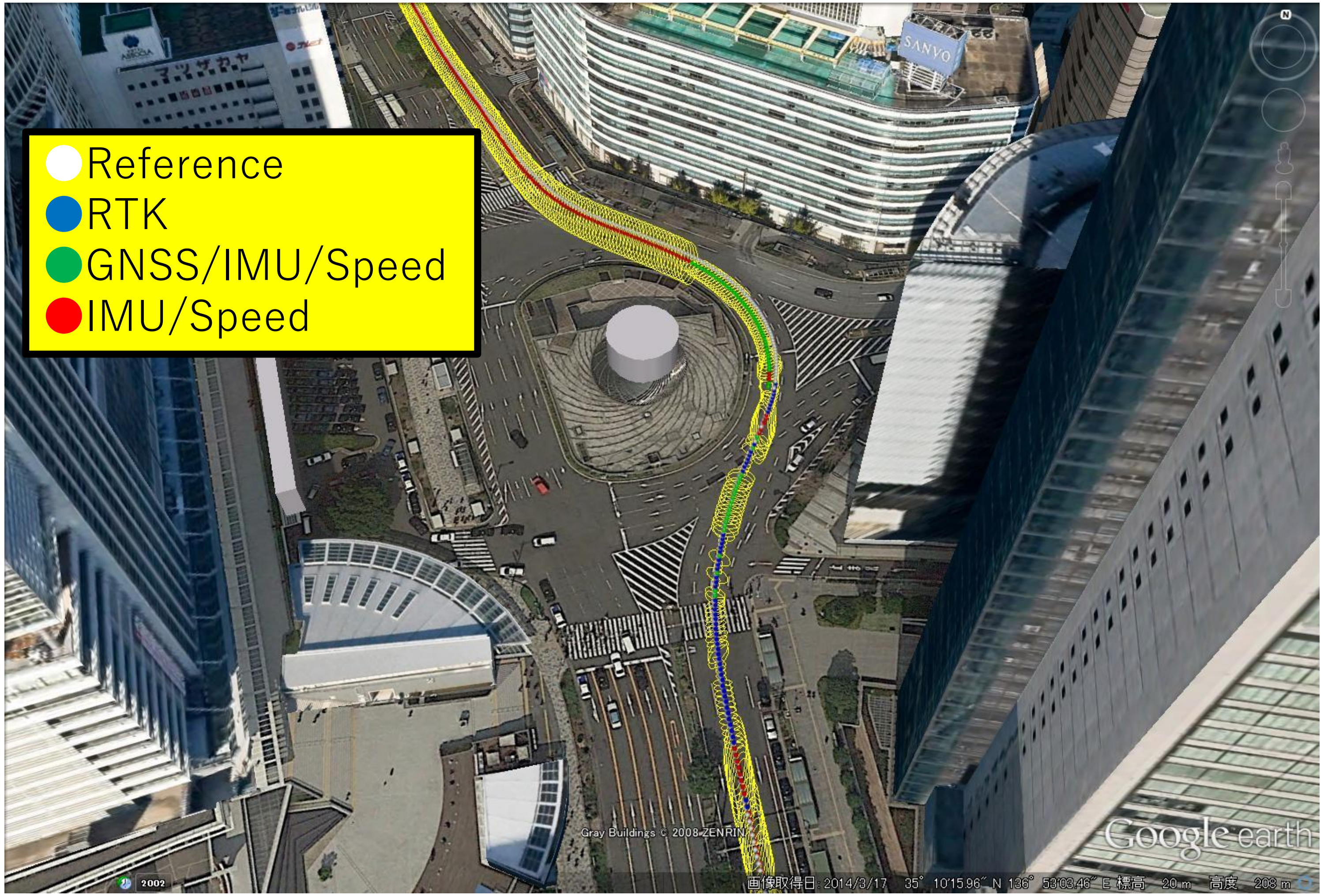
Presentation Outline

- Background
- Test results of commercial products
- Horizontal Protection Level for GNSS/IMU/Odometer
- Test results of our estimated HPL
- Summary

Confidence in Your Location

Smartphone tells you approximate confidence level of the position.



More reliable confidence level for automotive is required.

User Requests

Only GNSS

- Is GNSS position reliable ?
- Easily exceeds 1-2 m (+big jumps) in urban areas.

GNSS+IMU/Odometer

Odometer depends on the road condition.

- Is GNSS/IMU/Odometer position reliable ?
- Not easily exceeds 1-2 m (no big jumps) in urban areas.
- Integration with other sensors (Radar, Lidar, Camera…)

Integrity monitoring is one solution

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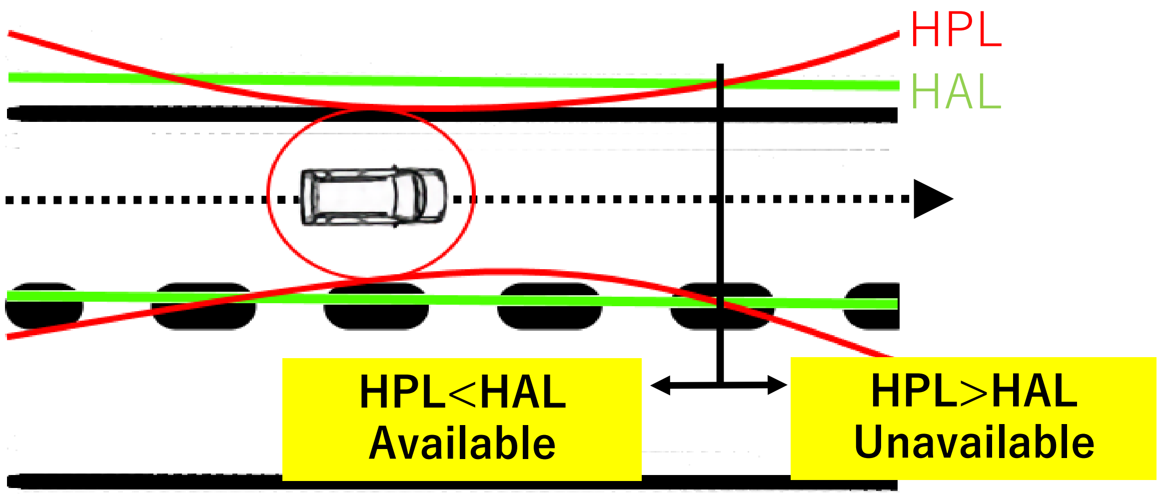
Integrity monitoring

Integrity

The ability of a navigation system to guarantee the absence of errors and to give an alarm when it should not be used for navigation. As a performance requirement, the probability that integrity is satisfied is defined.

The PL defines the confidence limits of the positioning error at the user's location. The confidence limit is called Protection Level (PL).
→HPL : Horizontal PL
VPL : Vertical PL

The protection level is compared with the AL (Alert Limit) to determine if the system can be used.

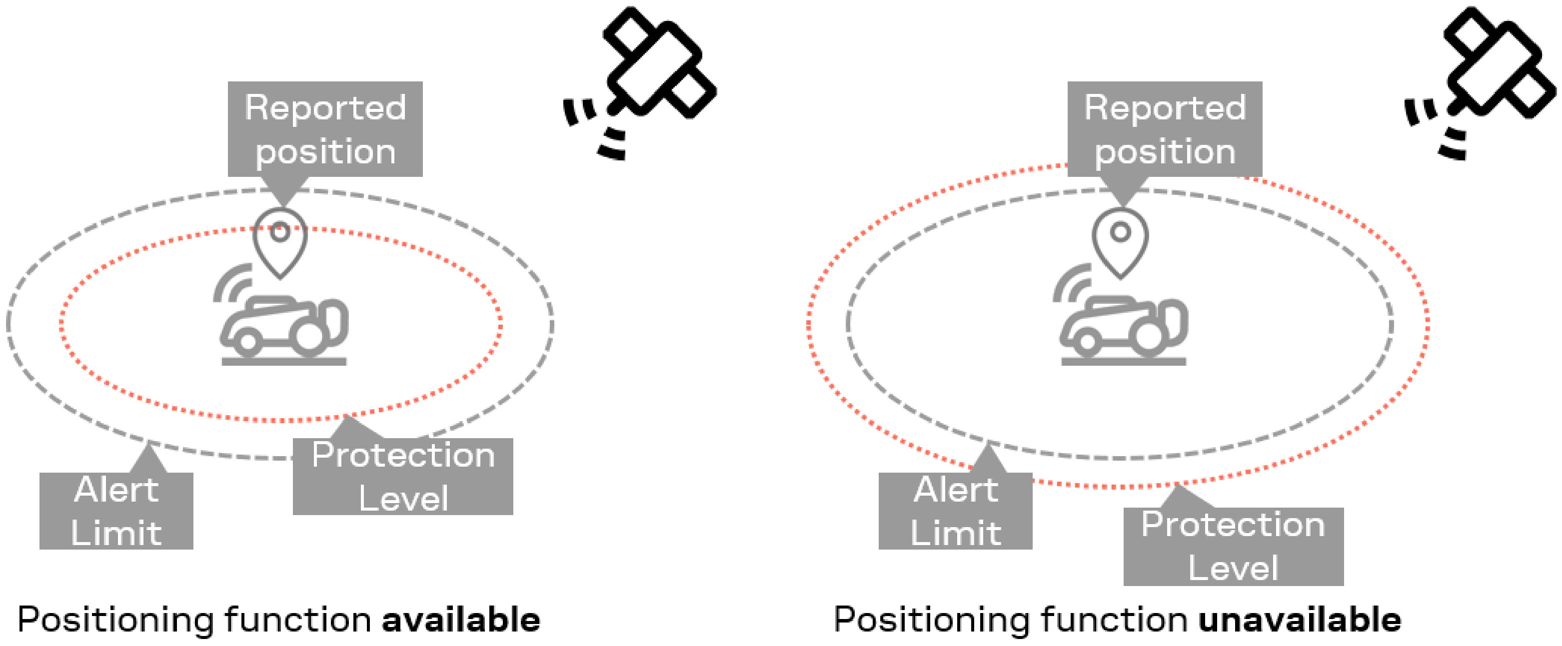


Approach of commercial receiver (only GNSS)

u-blox started to provide protection level (PL).

UBX-NAV-PL FW HPG1.30 (2021/12)

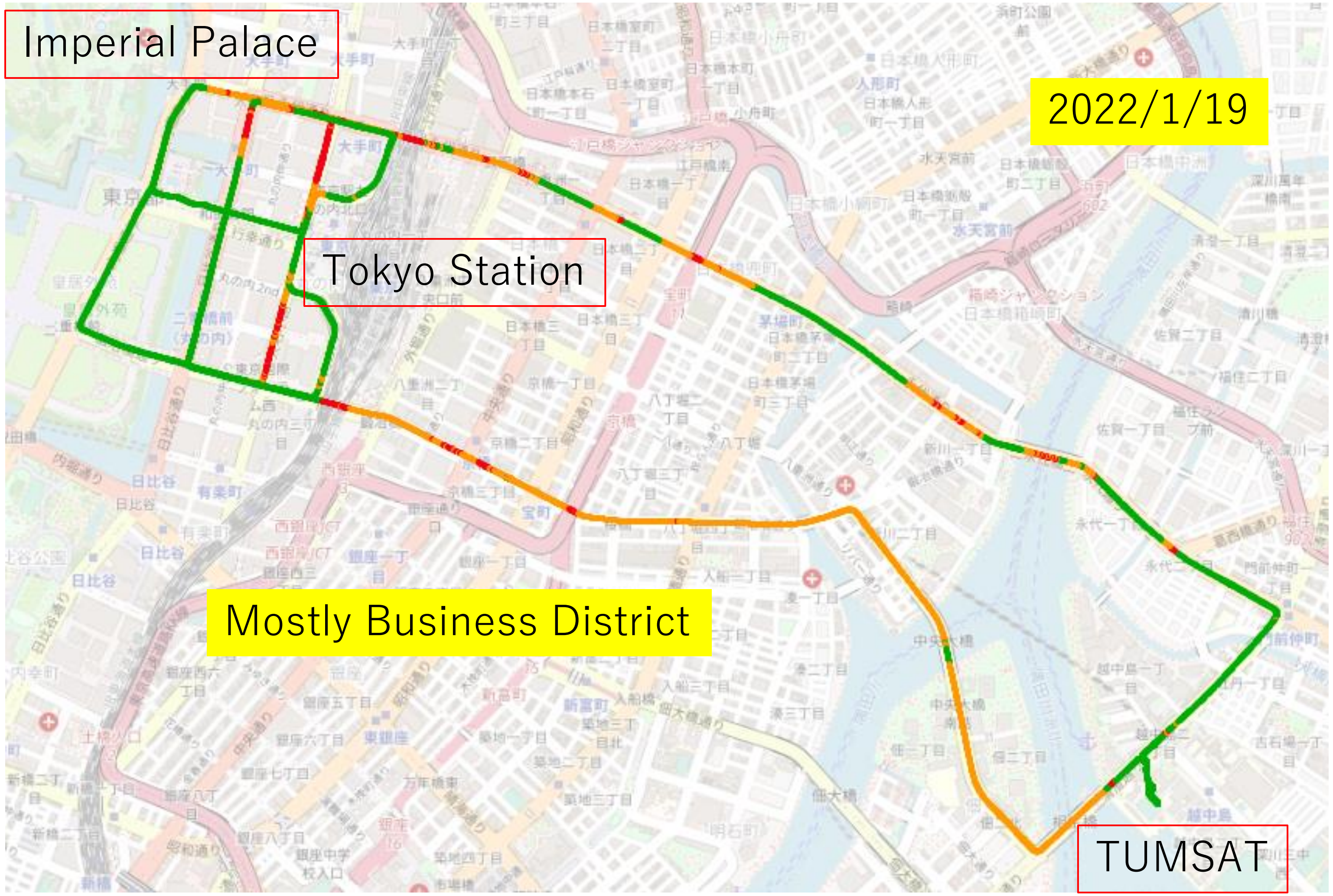
- TMIR(target misleading information risk)[%]
  Of all observed epochs, what percentage we will have over protection level ?
- **Receiver provides PL(Protection Level)[m, ENU]**



While basic protection levels add value to many consumer and industrial applications, critical automotive applications set much more stringent requirements on the protection level to achieve "functional safety." Automotive functional safety is defined in the ISO 26262 standard.

by u-blox

Car Test Results (F9P+JAVAD Ant.)



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Solutions:

Fix : 70.7%

Float : 25.8%

DGNSS : 3.4%

No Fix : 0.1%

Reference : POSLVX

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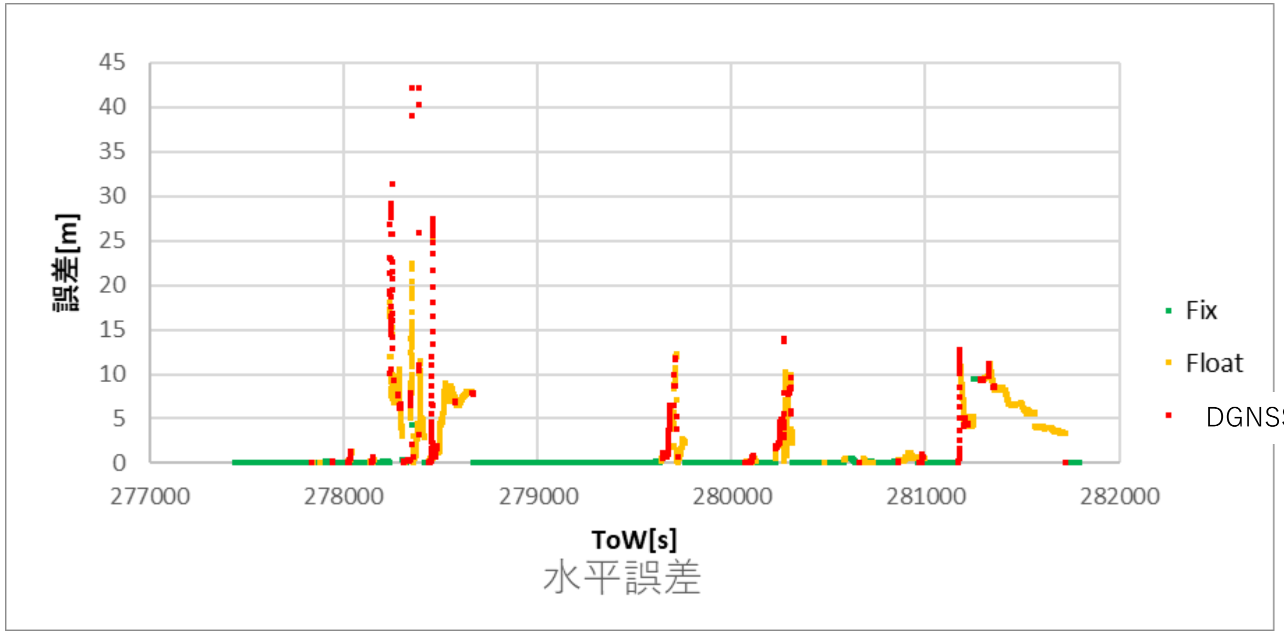
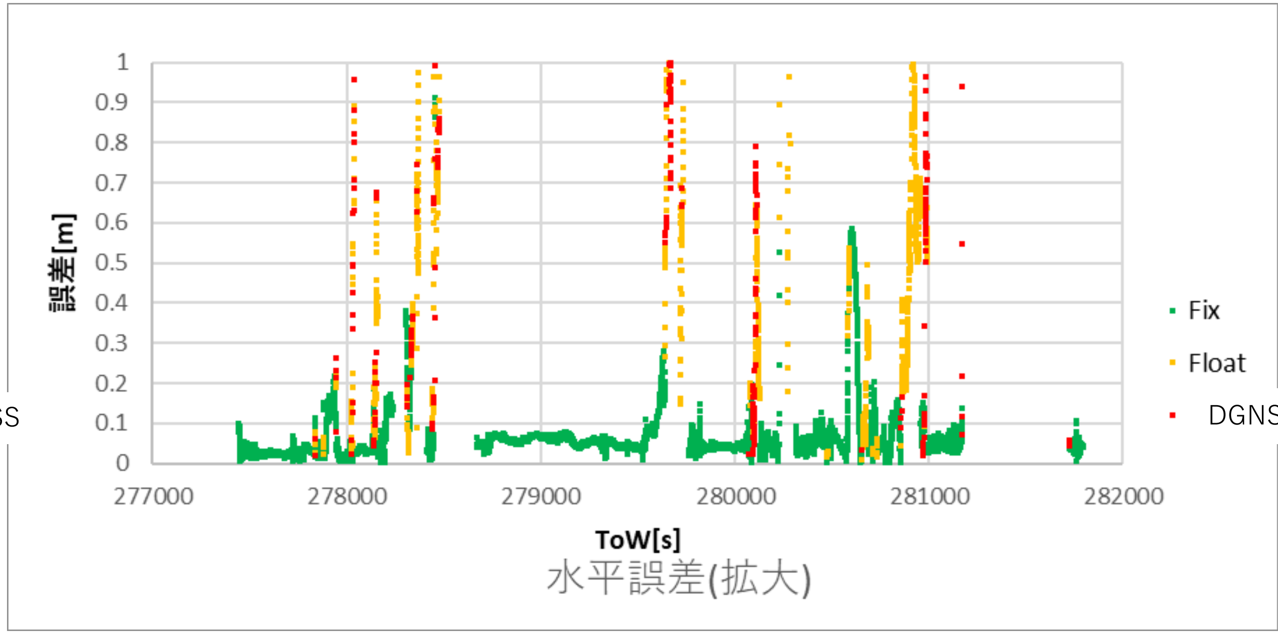
Actual Horizontal Errors



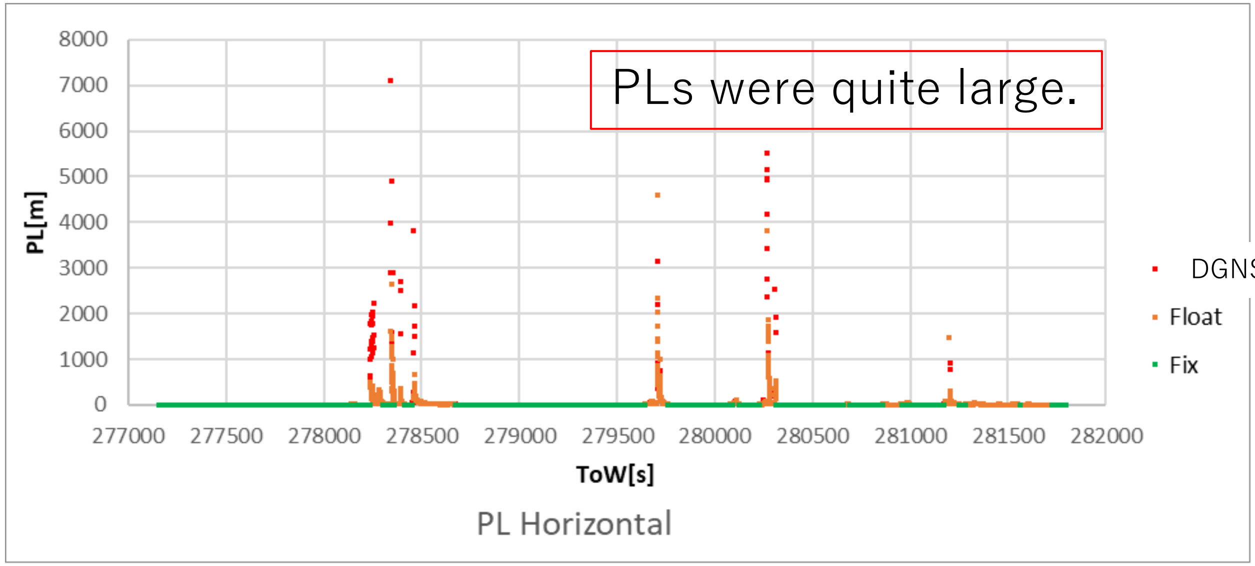
Absolute horizontal errors (m)

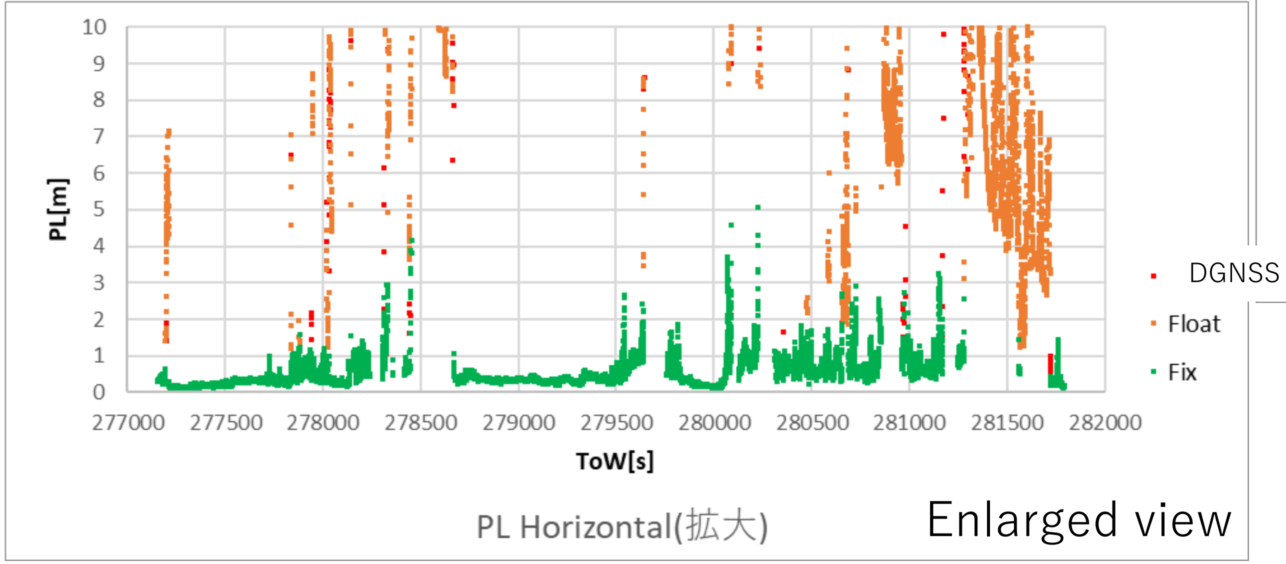


Absolute horizontal errors (m)

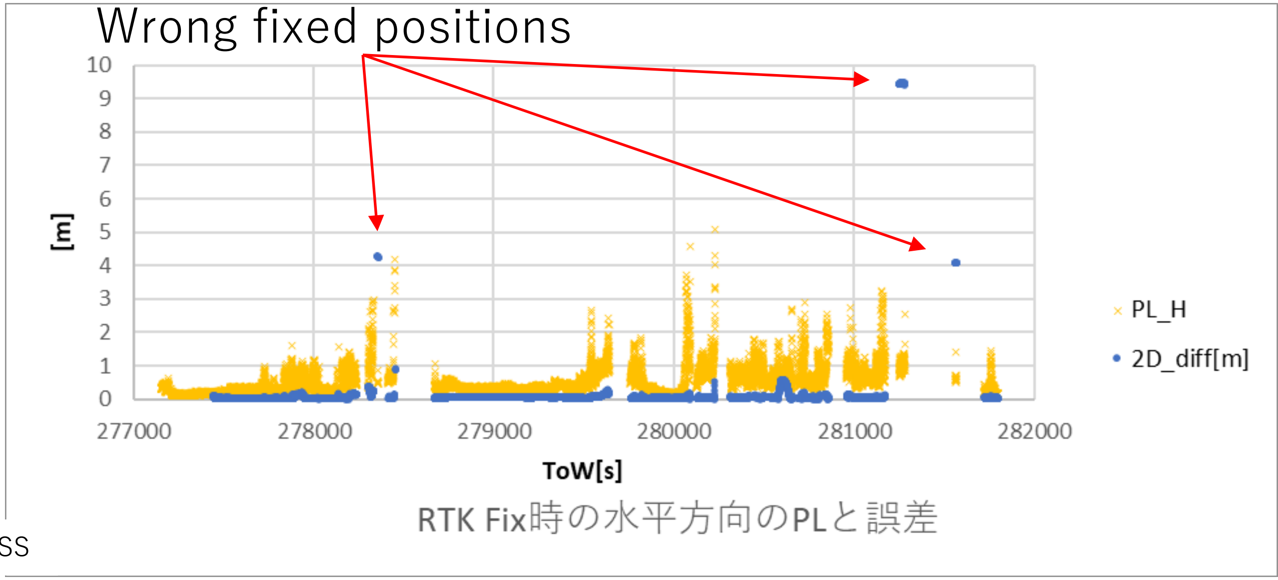
Enlarged view

Protection Levels in this Test





Comparison between Errors and PL (only RTK fixed)



Even for fixed solutions, PLs were over 1 m ?

Summary of this Test

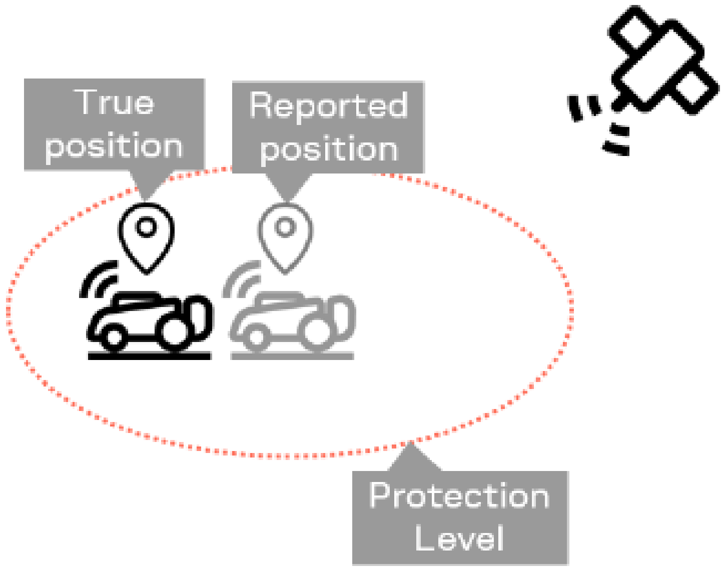


Figure 13: PL bounding true position error

	RTK Fix	FLOAT	DGNSS
PL>Error_N	98.6%	81.8%	100.0%
PL>Error_E	97.8%	77.1%	96.1%

<u>Our findings through tests (In total, 5 tests)</u>

1. PL in RTK fixed positions seems to be large.
2. FLOAT solutions are difficult to use.

Other sensors such as IMU/Odometer are definitely required.

Approach of commercial receiver (GNSS+sensors)

GNSS/IMU/Odometer (Applanix POS LVX)

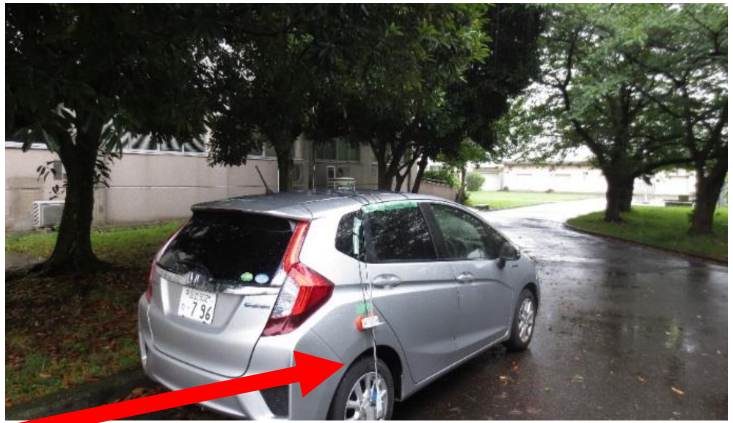
PERFORMANCE SPECIFICATIONS[4] (RMS ERROR)

No GNSS outages, standard road vehicle dynamics

	SPS	SBAS	RTK	Post-Processed[8]
Position (m)	1.5 H 3.0 V	0.1 H 0.5 V	0.02 H 0.03 V	0.02 H 0.03 V
Velocity	0.01	0.01	0.01	0.005
Roll & Pitch (deg)	0.04	0.03	0.03	0.025
True Heading[5](deg)	0.12	0.09	0.09	0.06

1 km or 1 minute GNSS outage, standard road vehicle dynamics[6]

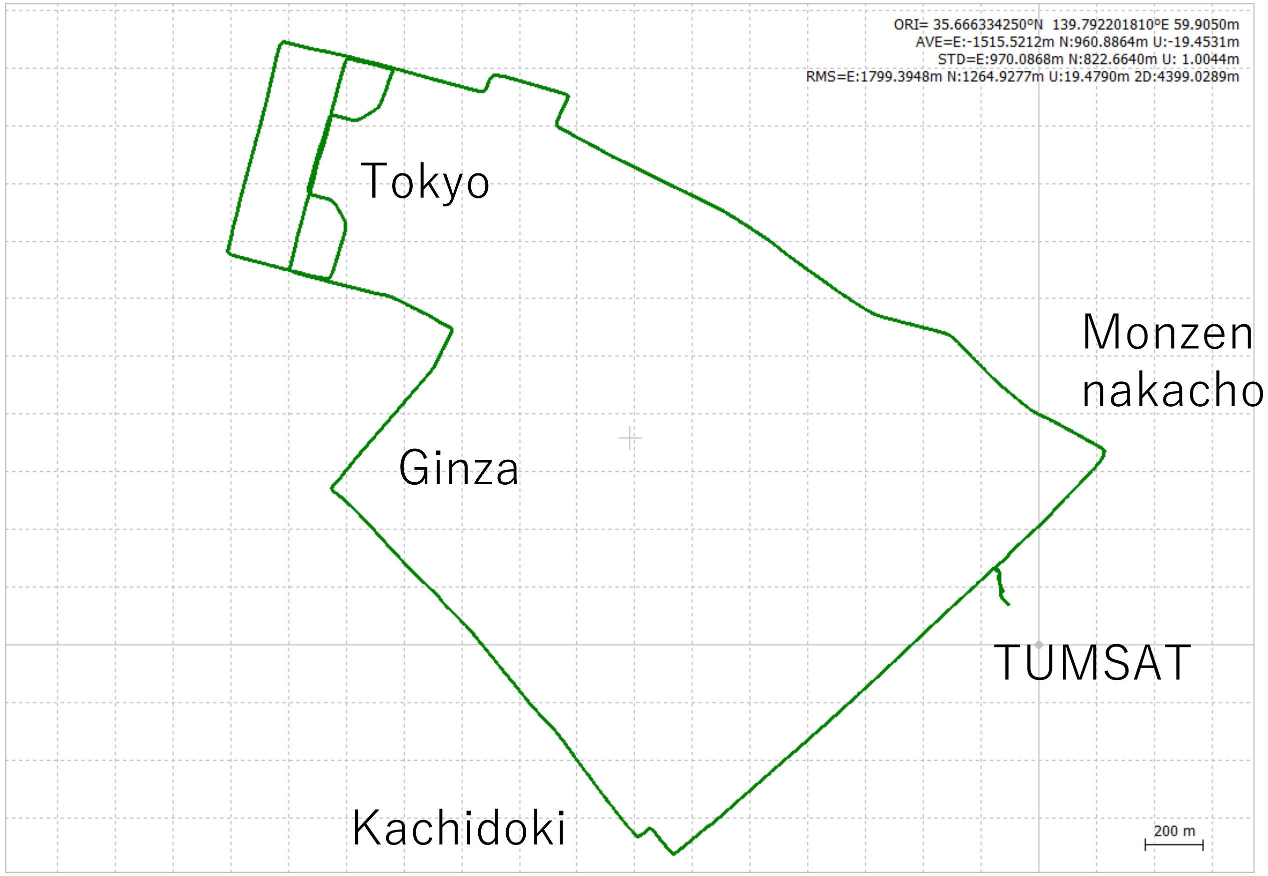
	SPS	SBAS	RTK	Post-Processed[8]
Position (m)	2.0 H 5.0 V	2.0 H 3.0 V	1.0 H 2.0 V	0.80 H 0.20 V
Roll & Pitch (deg)	0.09	0.09	0.09	0.05
True Heading[5] (deg)	0.35	0.35	0.30	0.20



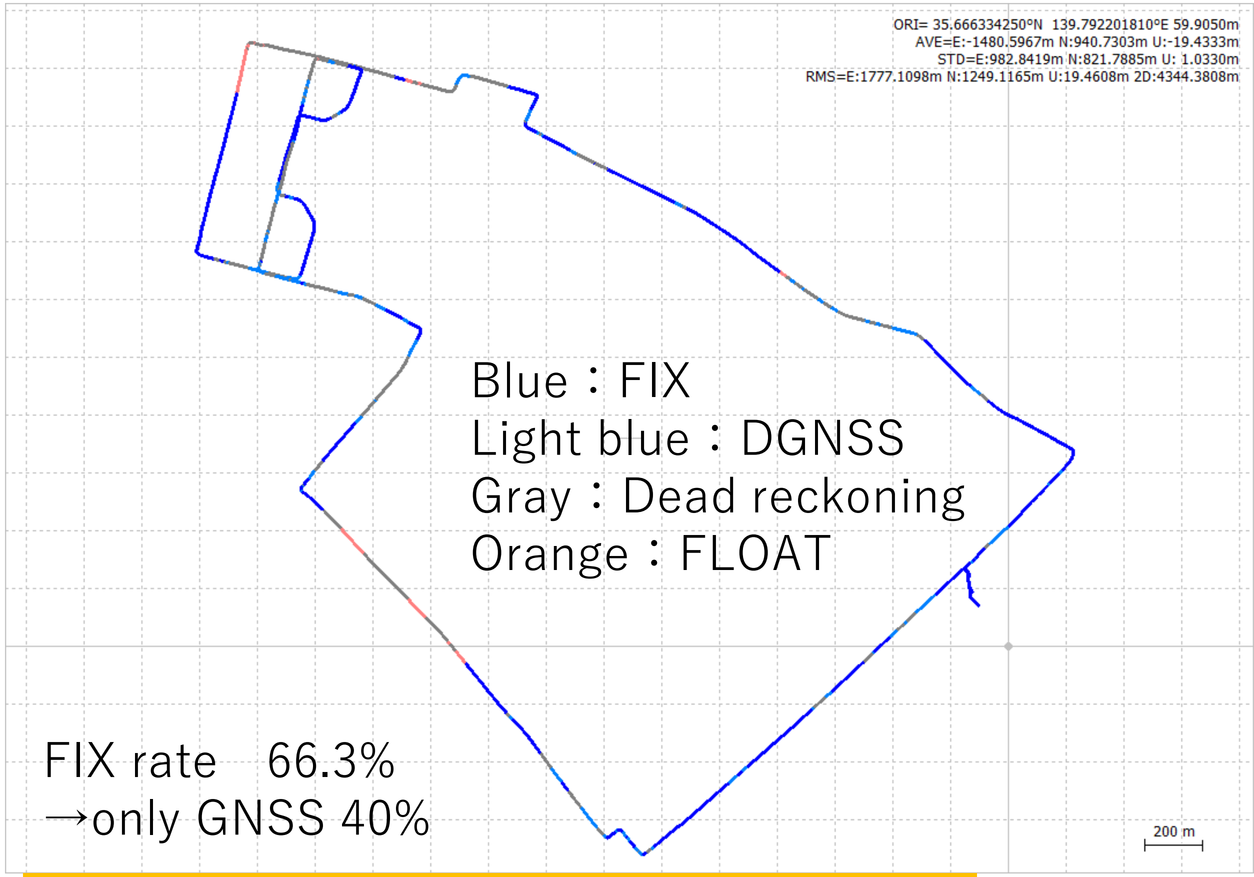
Wheel odometer

Integration performance (dense urban case)

Post-processed

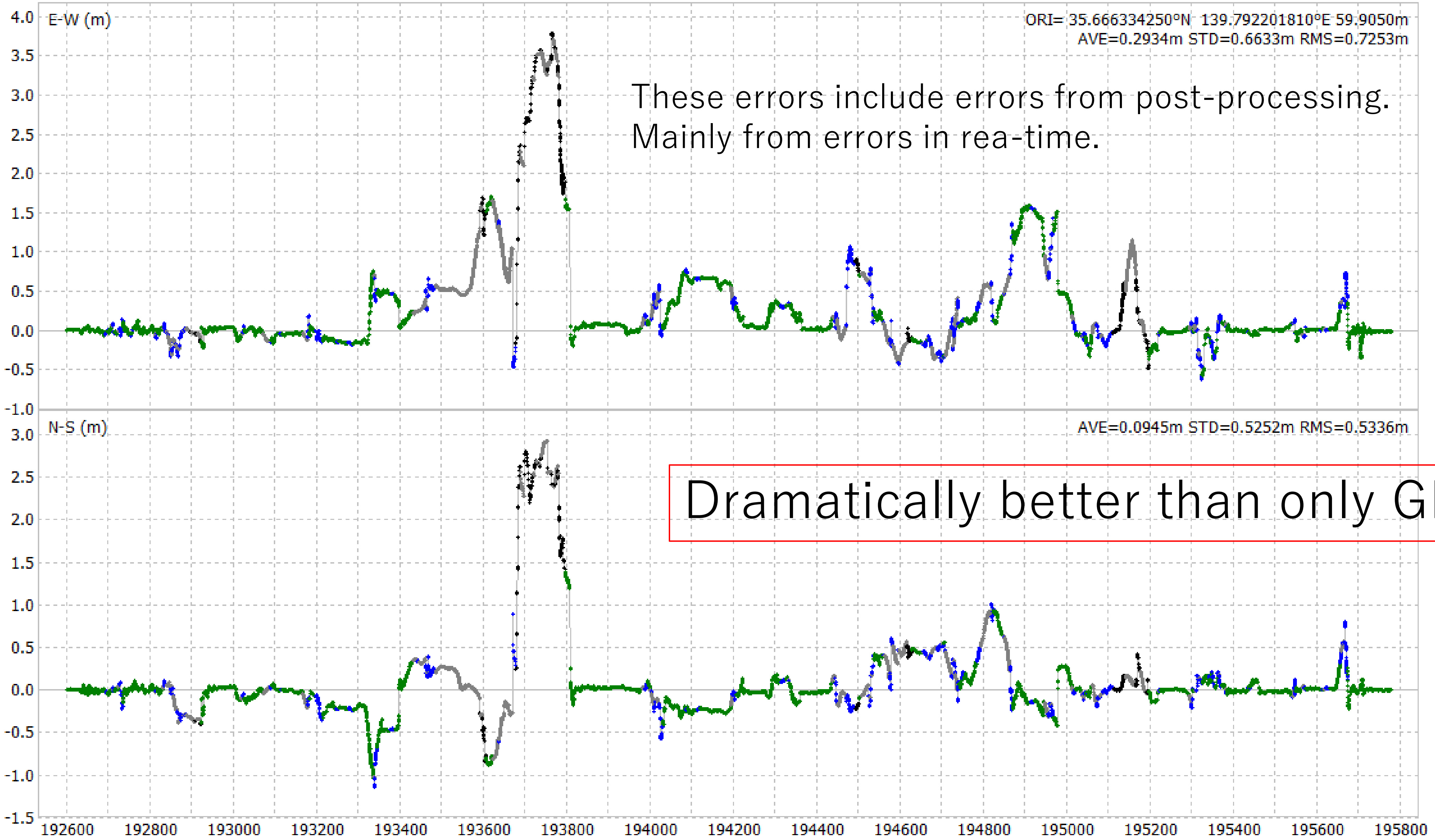


Real-time



FIX rate is improved by integrating GNSS with IMU/Odometer.

Actual difference : Post processed and Real-time



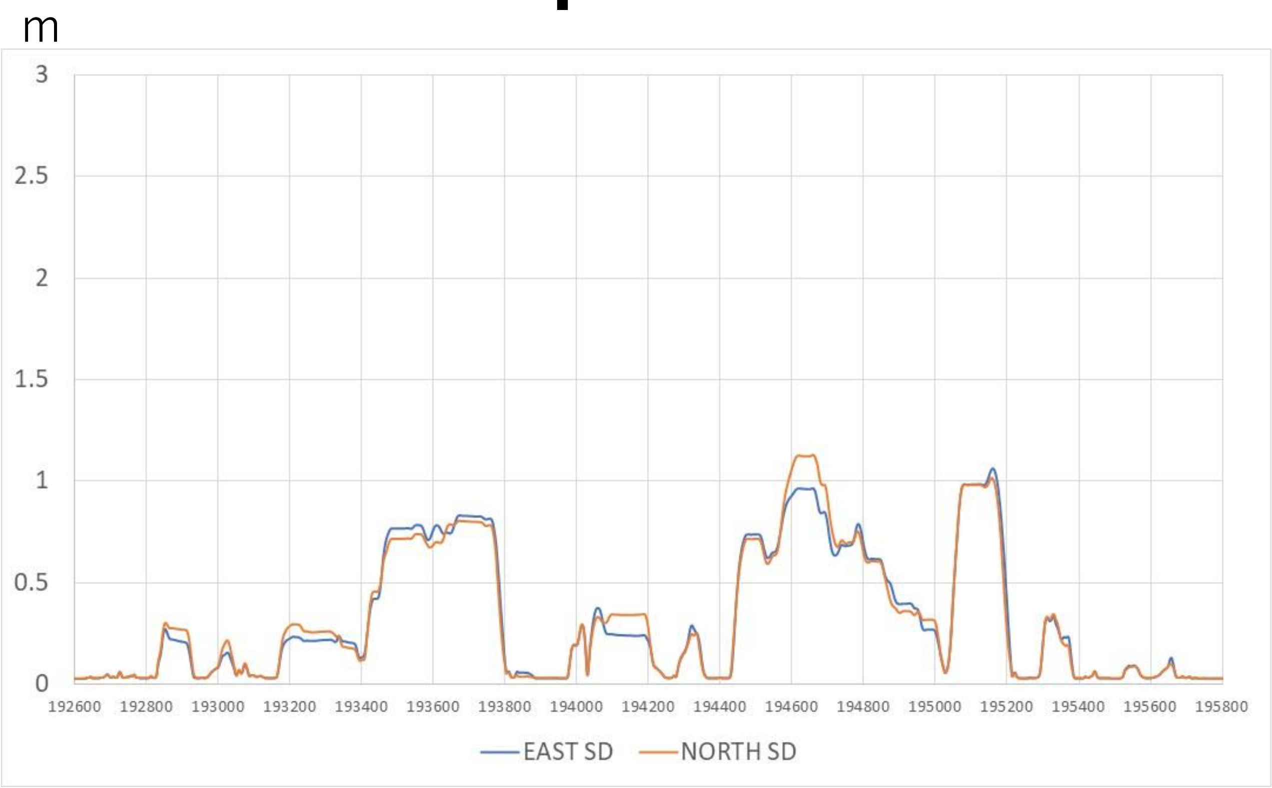
These errors include errors from post-processing.
Mainly from errors in rea-time.

Dramatically better than only GNSS.

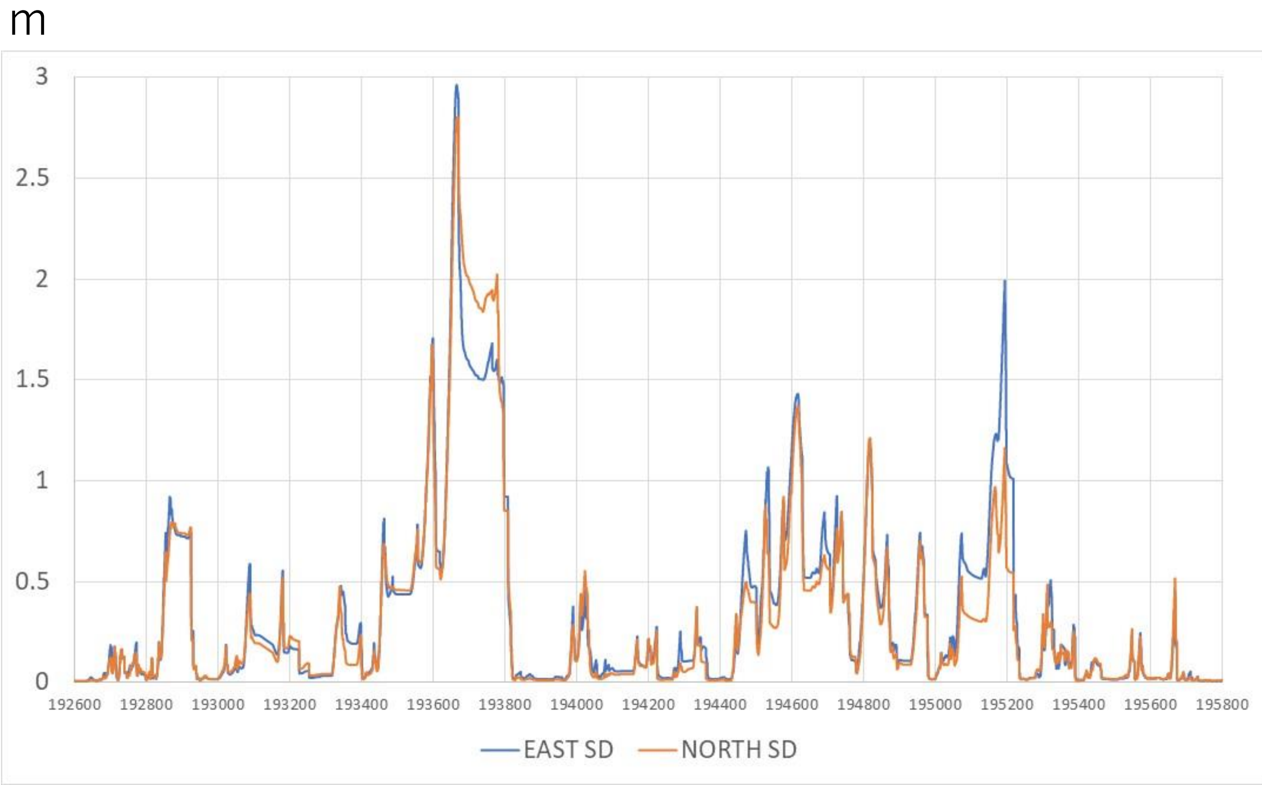
Horizontal RMS values for post-processed, real-time

POSLVX provides RMS (SD) values simultaneously.

Post-processed



Real-time



Relatively large error (normally 60-70cm in maximum)

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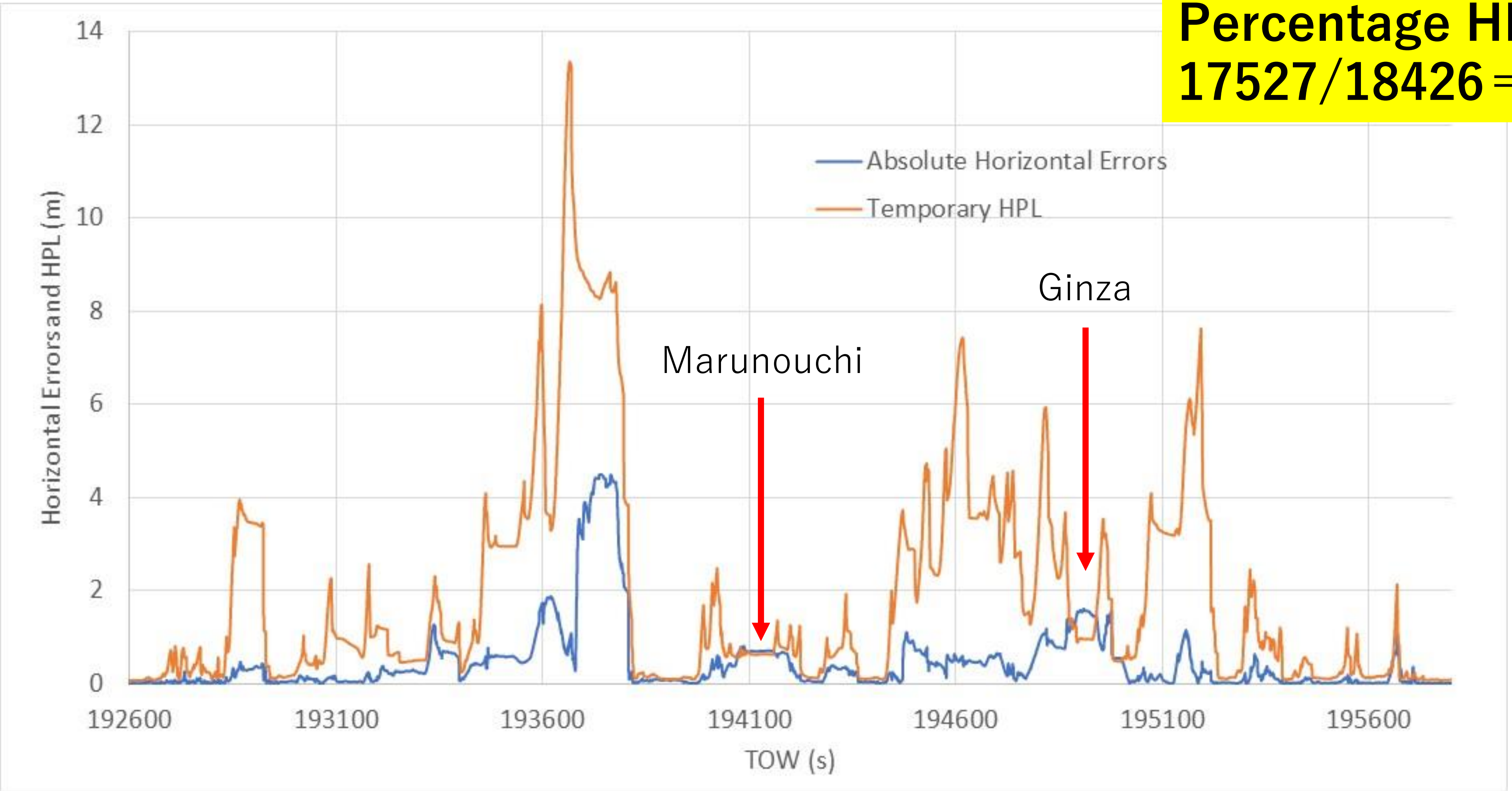
PL＝Post-RMS＋Real-time RMS×3

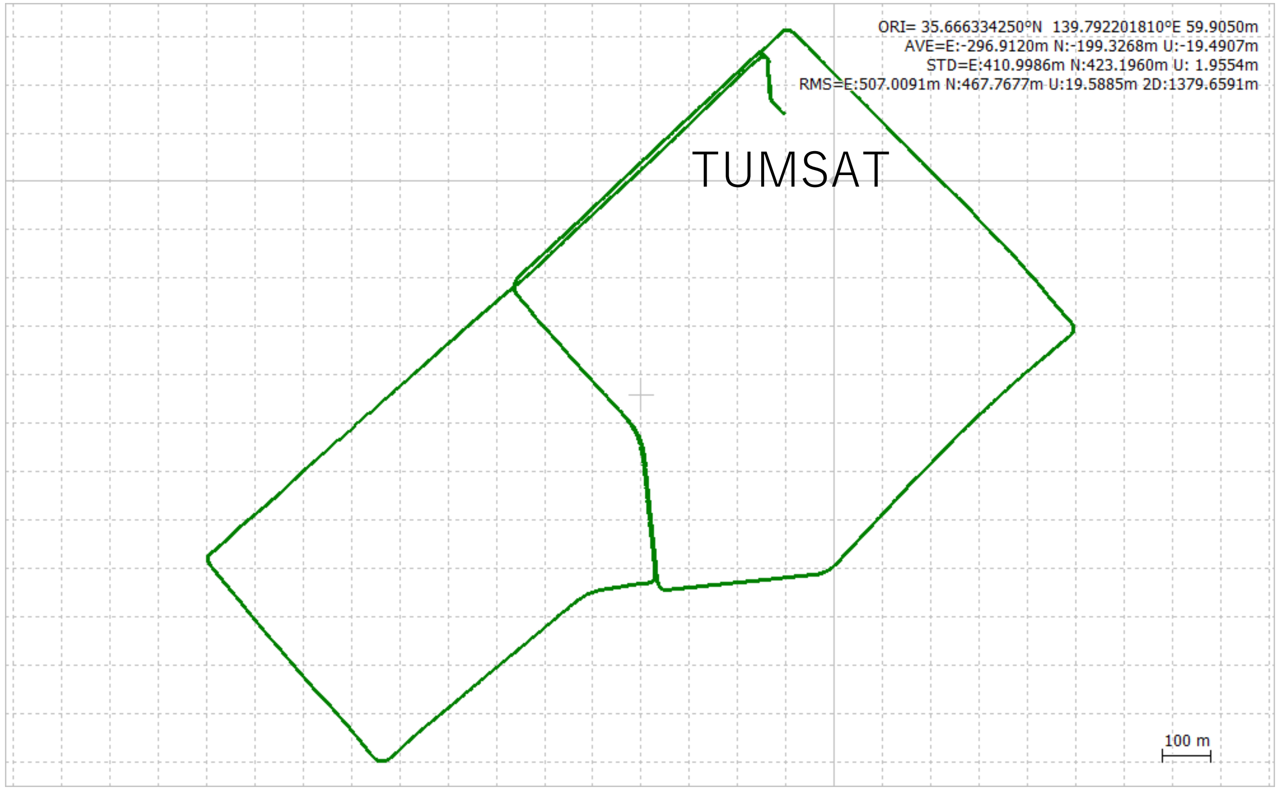
Generated a temporary protection level.
Orange : Protection level(HPL), Blue : Actual errors (HE)

Percentage HPL＞HE
17527/18426＝95.1%

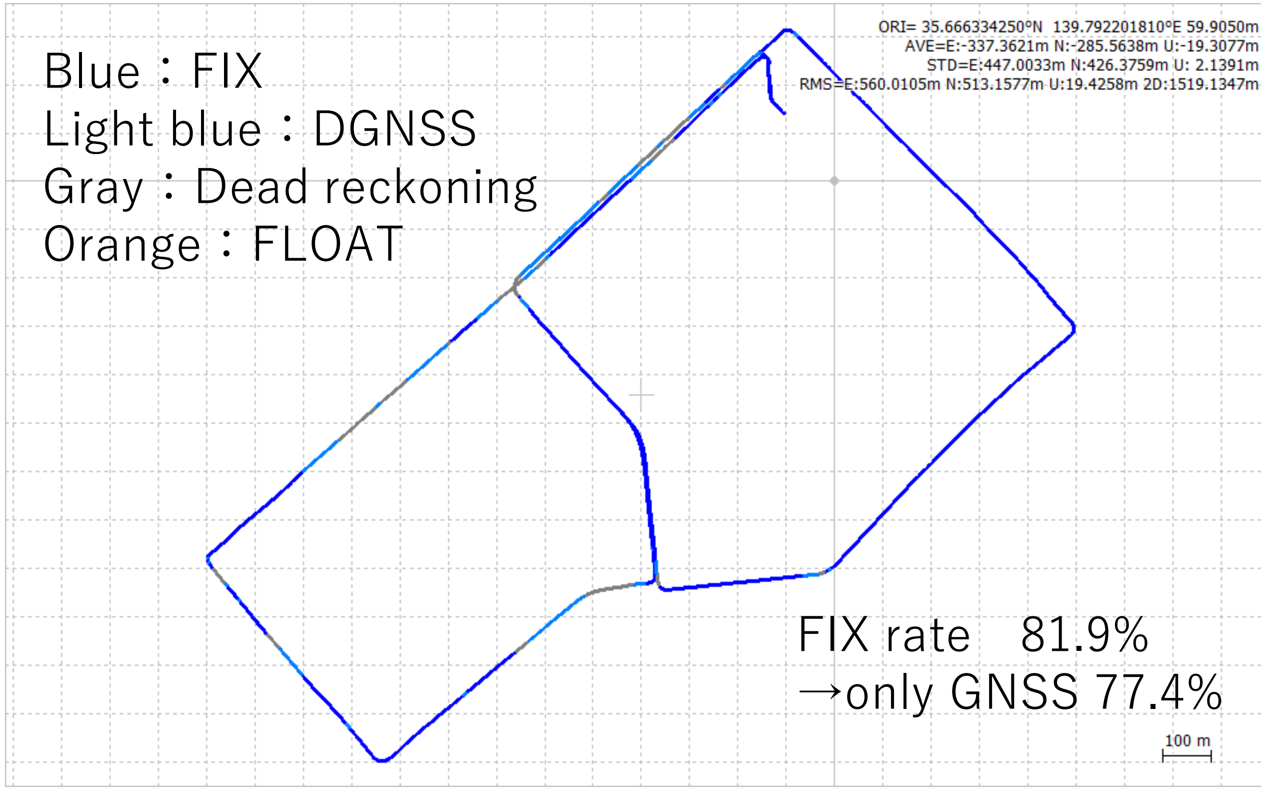


Integration performance (semi urban case)

Post-processed

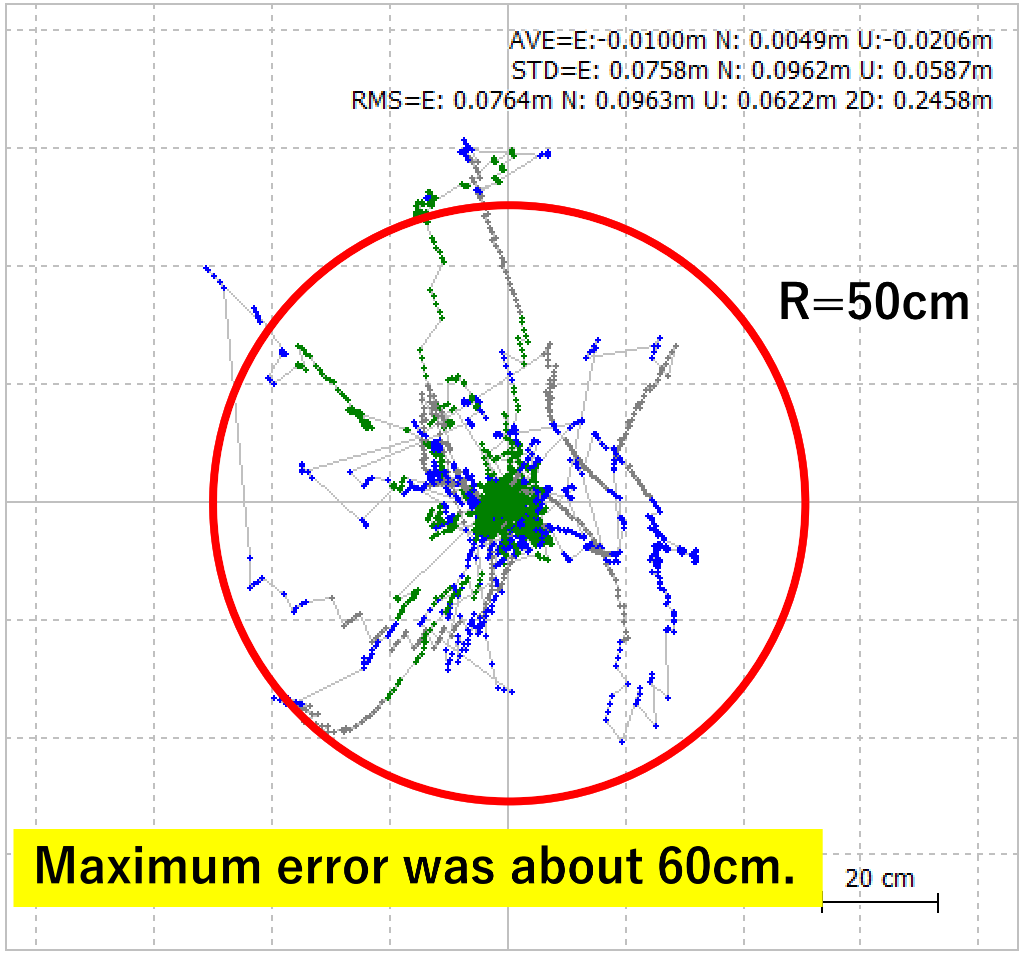


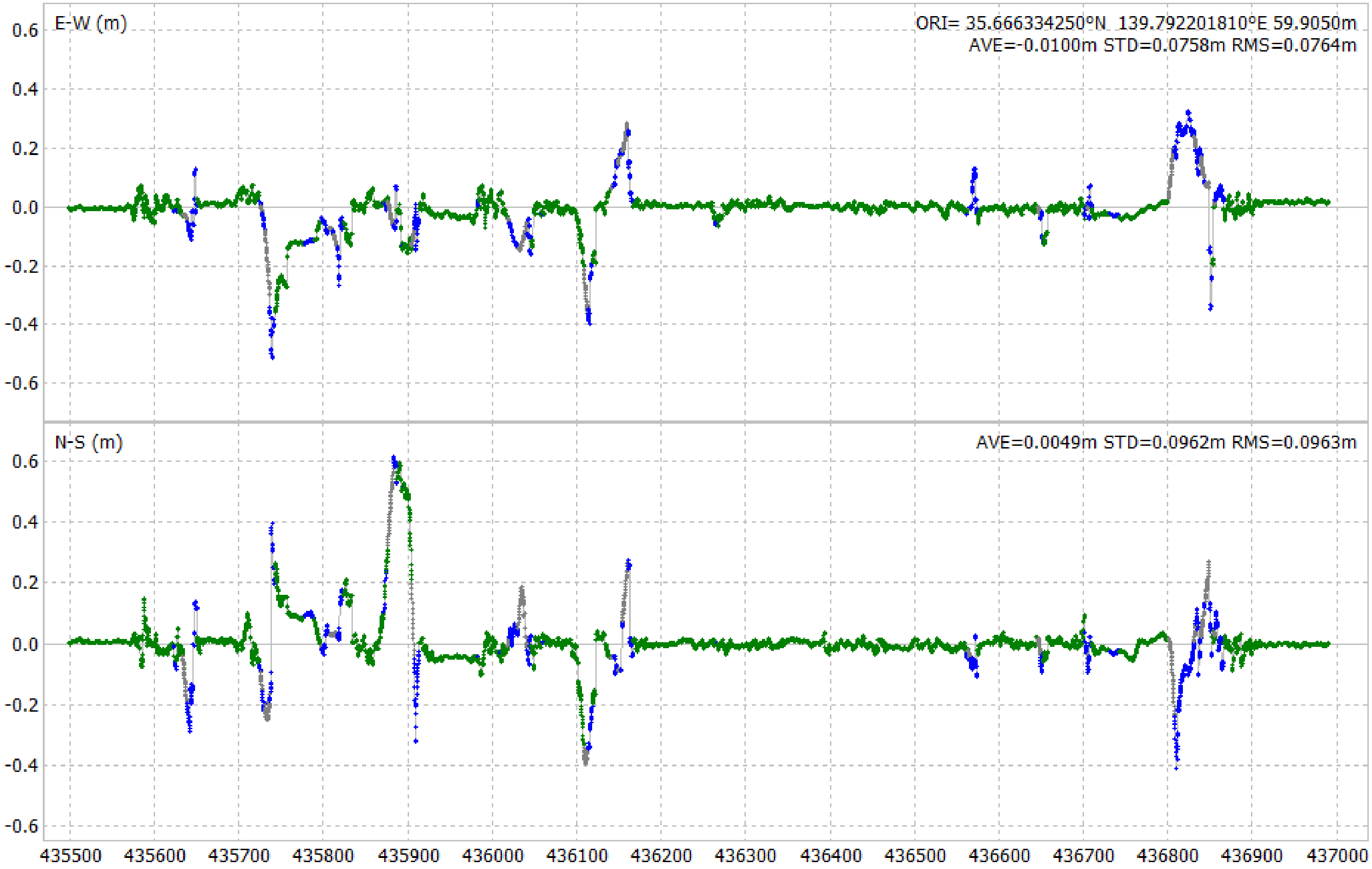
Real-time



<u>Multipath errors are less than the previous case (dense urban)</u>

Actual difference : Post processed and Real-time



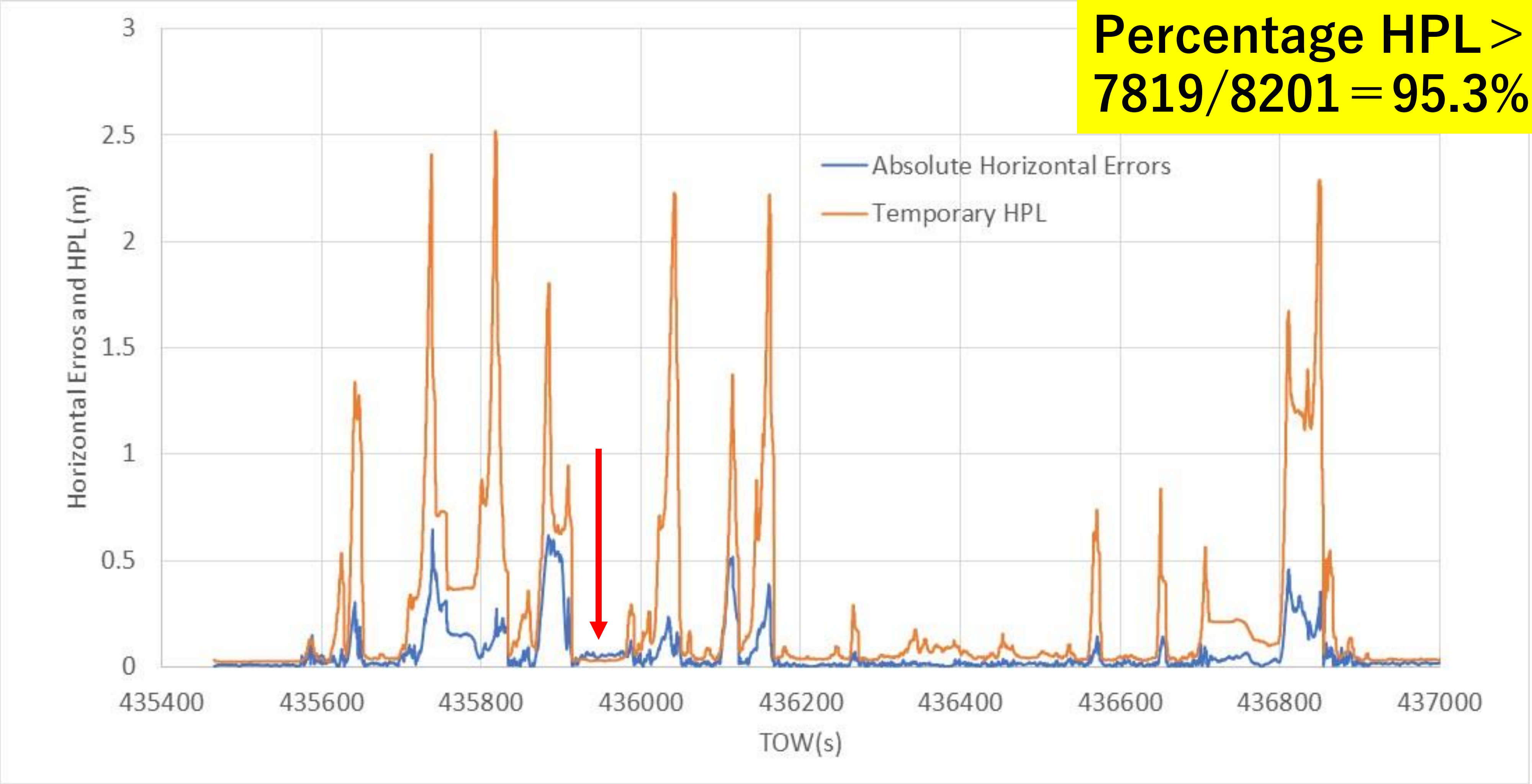


Accuracy is different from the results of dense urban.

PL＝Post-RMS＋Real-time RMS×3

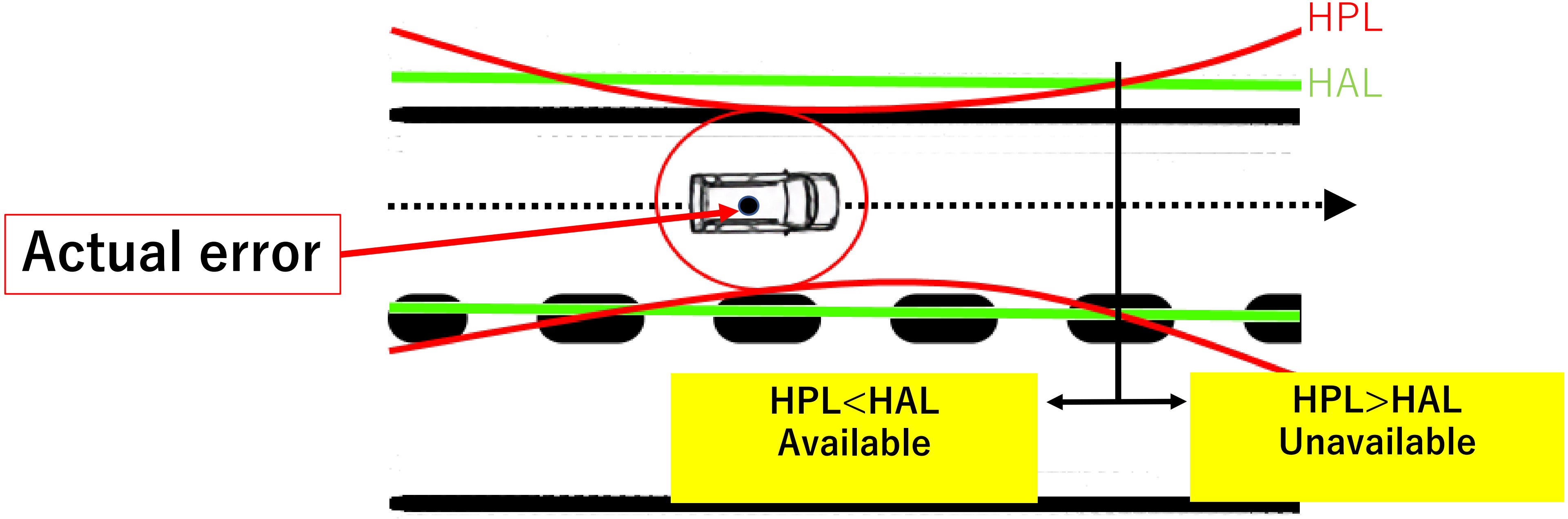
Generated a temporary protection level.
Orange : Protection level (HPL), Blue : Actual errors (HE)

Percentage HPL＞HE
7819/8201＝95.3%



HPL estimation for GNSS/IMU/Odometer

HPL have to provide an upper bound of the actual error.



Features of each sensor

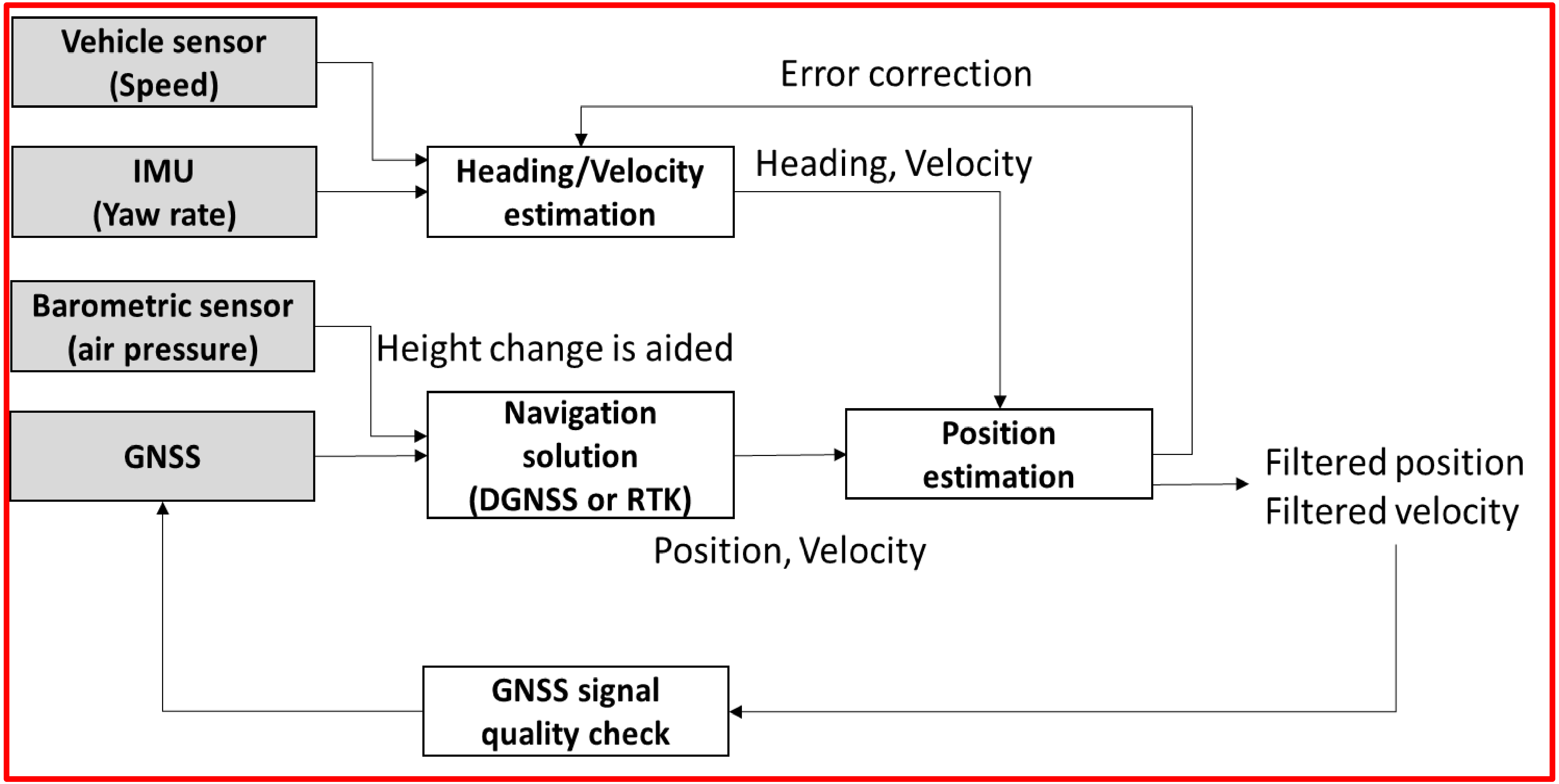
GNSS
IMU/Odometer

Integration

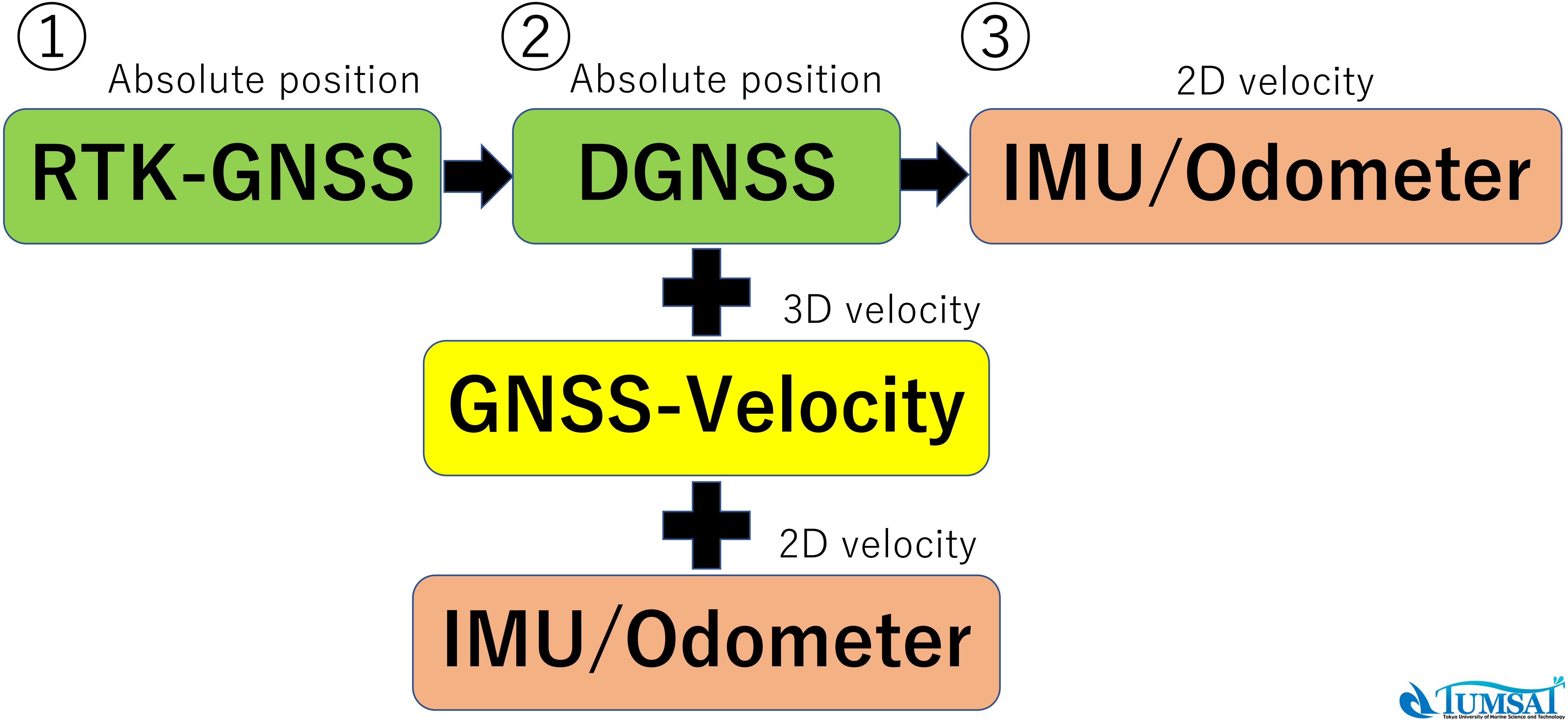
Good and bad of each sensor

	GNSS			External sensors	
	RTK	Velocity	DGNSS	Odometer	IMU
Position	○	-	△	-	-
Velocity	○	○	×	○	×
Direction	△	△	×	-	△

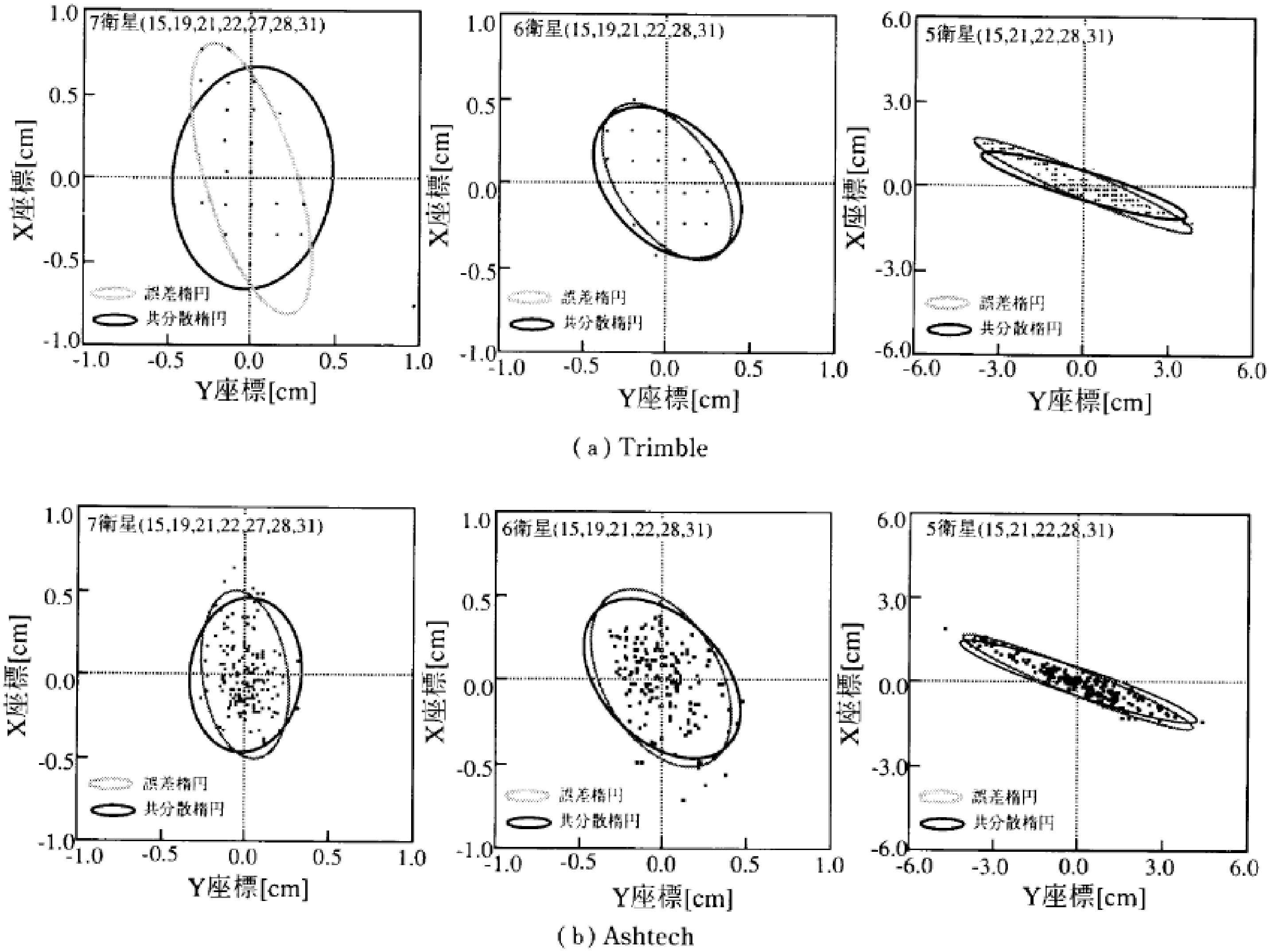
GNSS/IMU/Odometer Integration



Priorities for PL



1. Error Ellipse of RTK-GNSS



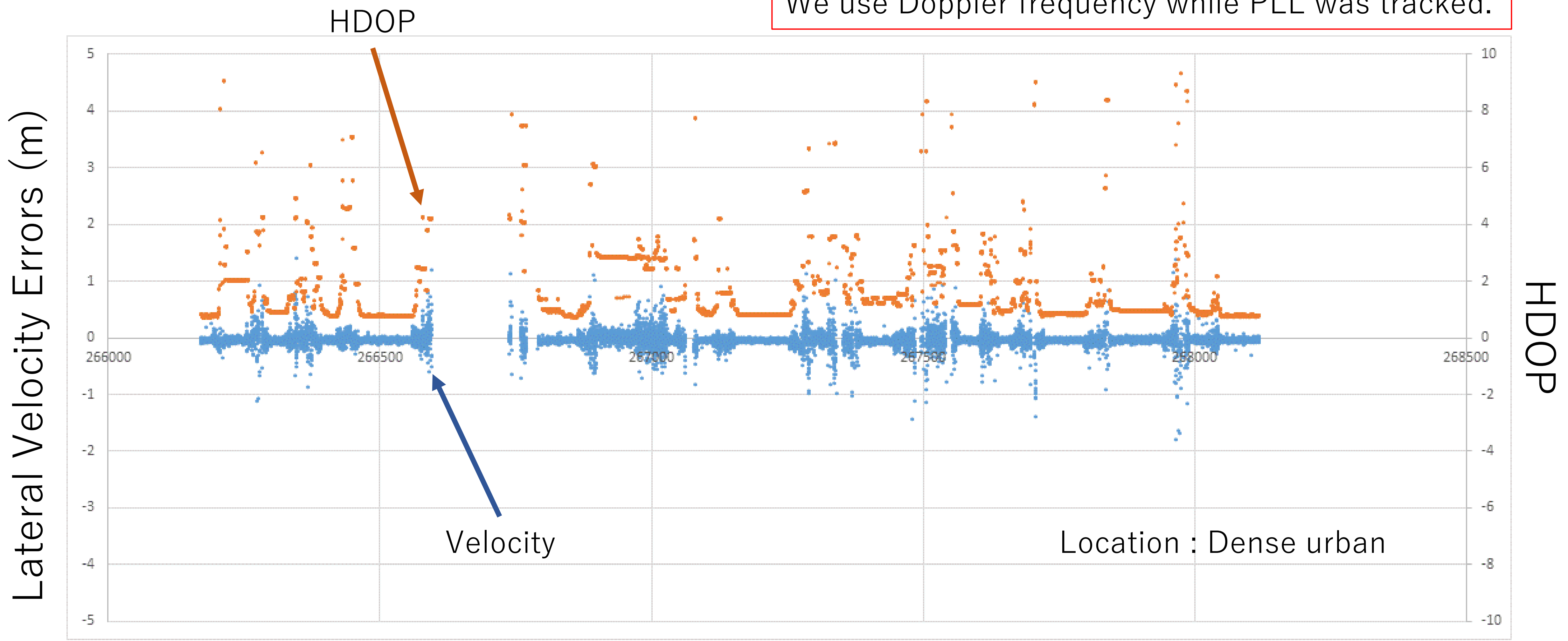
Predicted error ellipse of RTK-GNSS based on DOP covers those real errors very well.

$HPL_{(RTK\text{-}GNSS)} = HDOP * A * \sigma_{(RTK\text{-}GNSS)}$

A is coefficient (ex. 3σ)
σ depends on C/N_0 (2-5cm)
RMS of Reference position is considered.

Doppler/Carrier based velocity and HDOP

We use Doppler frequency while PLL was tracked.



HDOP is <u>somehow related to</u> the error of GNSS velocity.

2. GNSS(POS/VEL) + IMU + Odometer

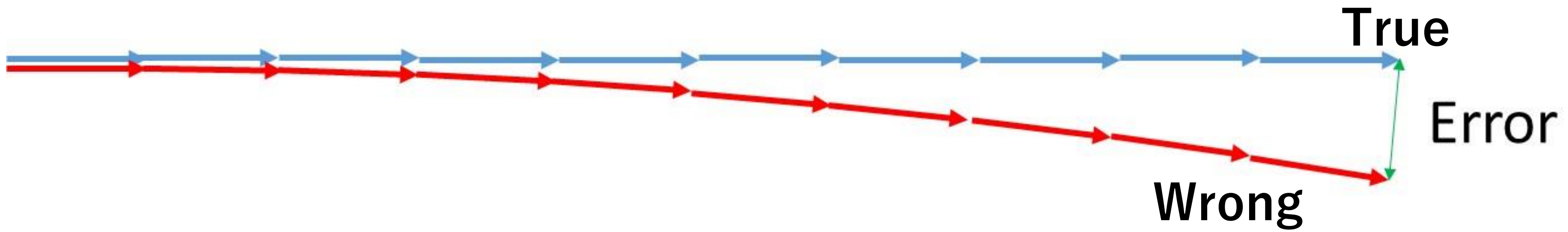
- We coupled DGNSS with Velocity using KF.
- We will see GNSS based 2D velocity by comparing 2D velocity from IMU/Odometer.
- If we see large errors, we can rely on IMU/Odometer.
- Next position will be predicted by previous position + velocity vector.
- We always see the gap between GNSS based position with this predicted position.
- If we see large gap, we rely on predicted position.

$HPL_{(GNSS+IMU+Odometer)}$ = Estimated error from KF (POS. is valid)
$HPL_{(GNSS+IMU+Odometer)}$ = is accumulated by the estimated error of the velocity (POS. is not valid)
Coefficient is added.

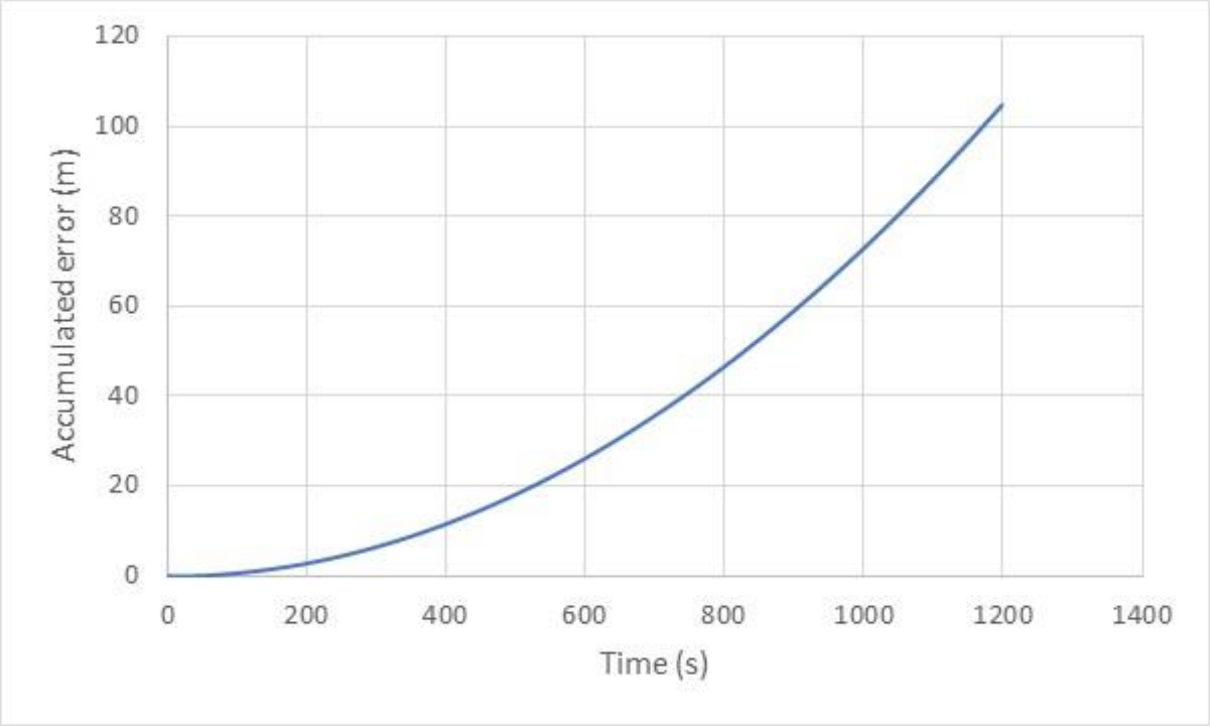
3. IMU + Odometer (Dead-reckoning)

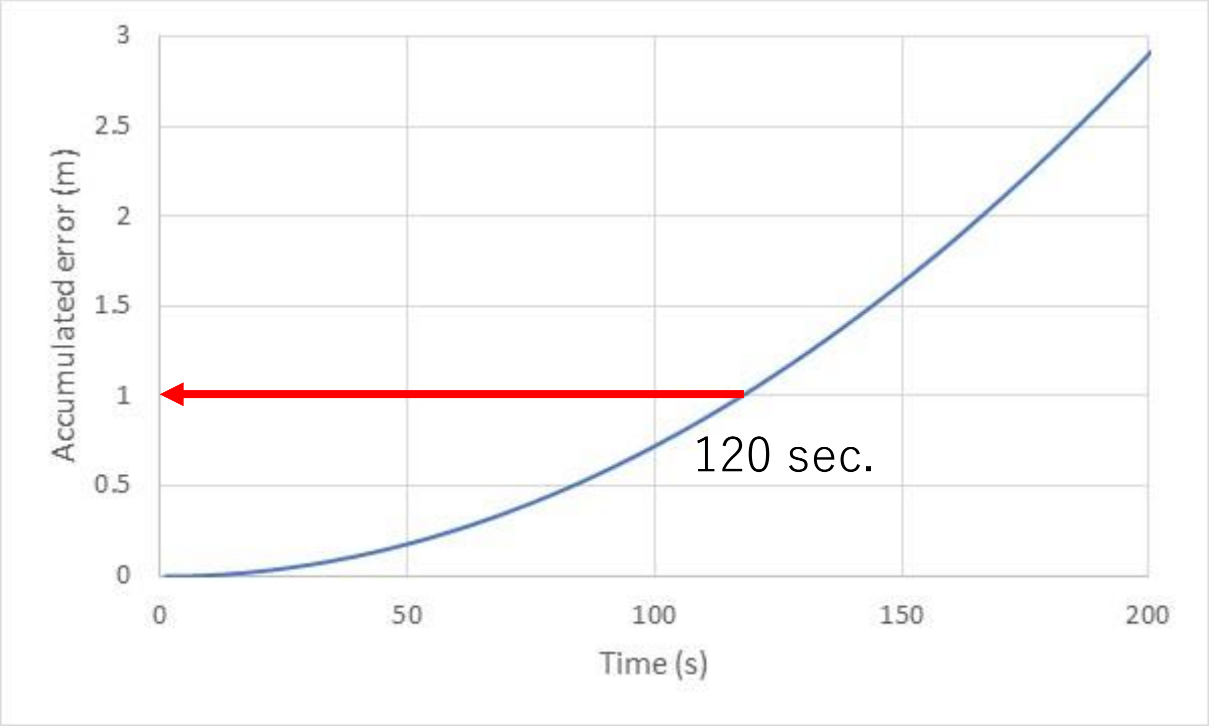
- It depends on the speed of the car.
- Resolution of the speed pulse.
- The bias of the speed should be removed.
- Bias stability of gyro sensor (YAW) should be checked.
- Bias is removed by ZUPT.
- <u>1 deg. / 20 min. with 5 m/s</u> → approx. 105m error in 20min.

$HPL_{(IMU+Odometer)}$ = is accumulated by the estimated bias stability Coefficient is added.



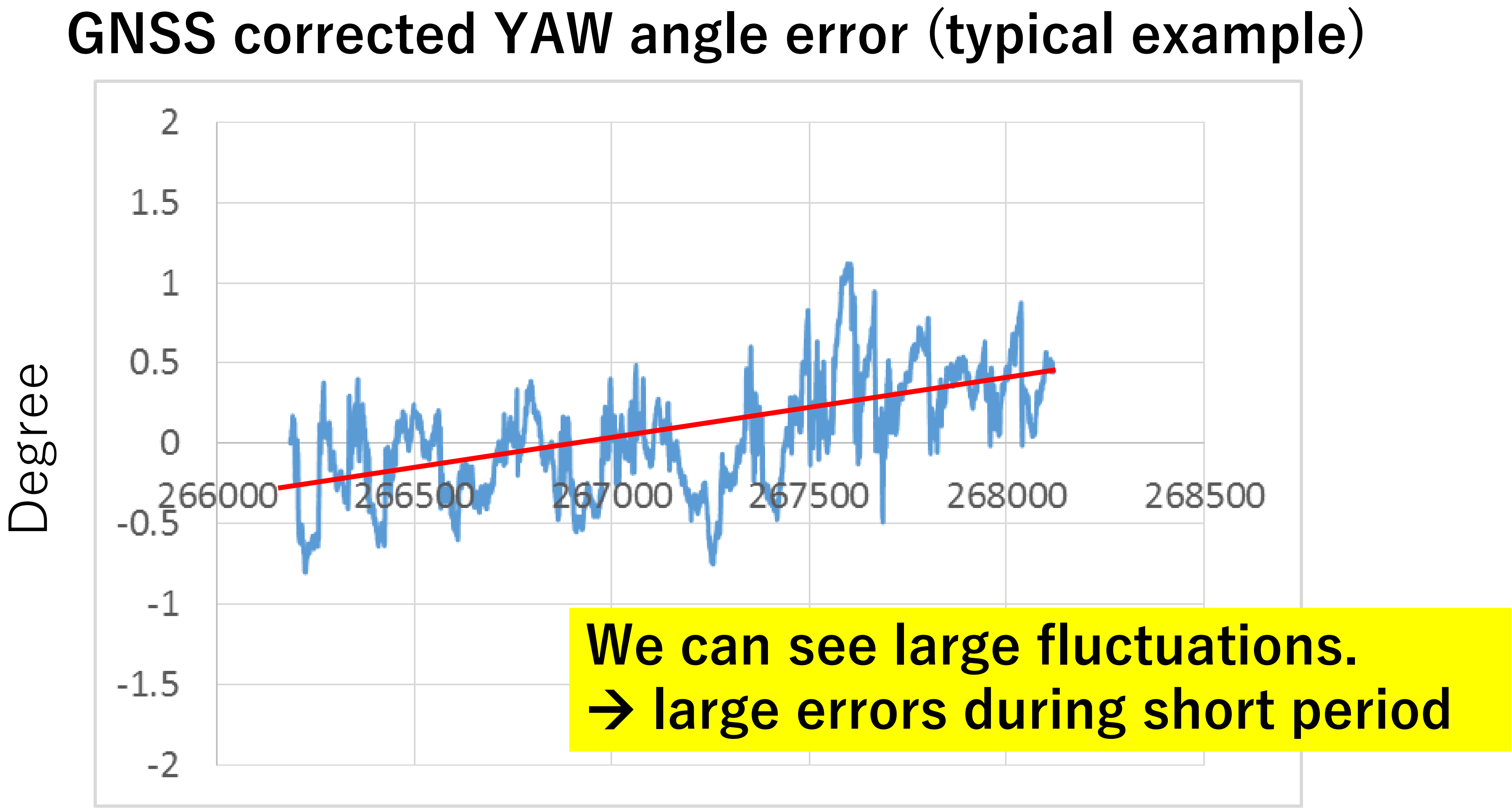
1.0 deg.(YAW) / 20 min. with 5 m/s -simulation-





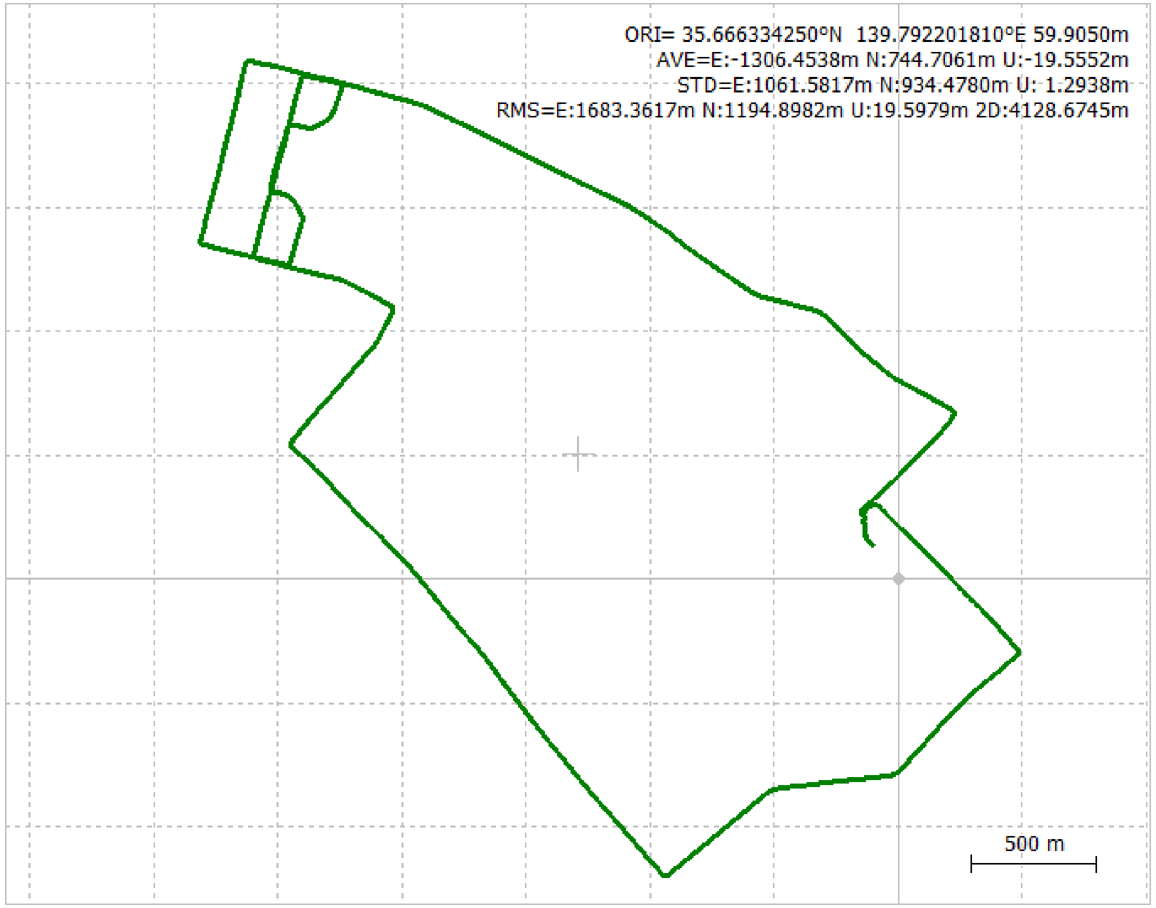
- **IMU sensor used in our lab. is similar to this in total but it is also important to see the bias in short period.**

Typical behavior of the actual YAW Error



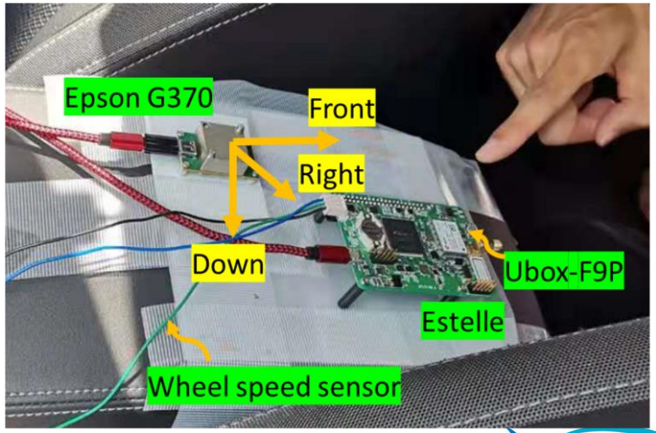
0.7 deg. in 30 min. in total. However,…

Test Results (dense urban case)

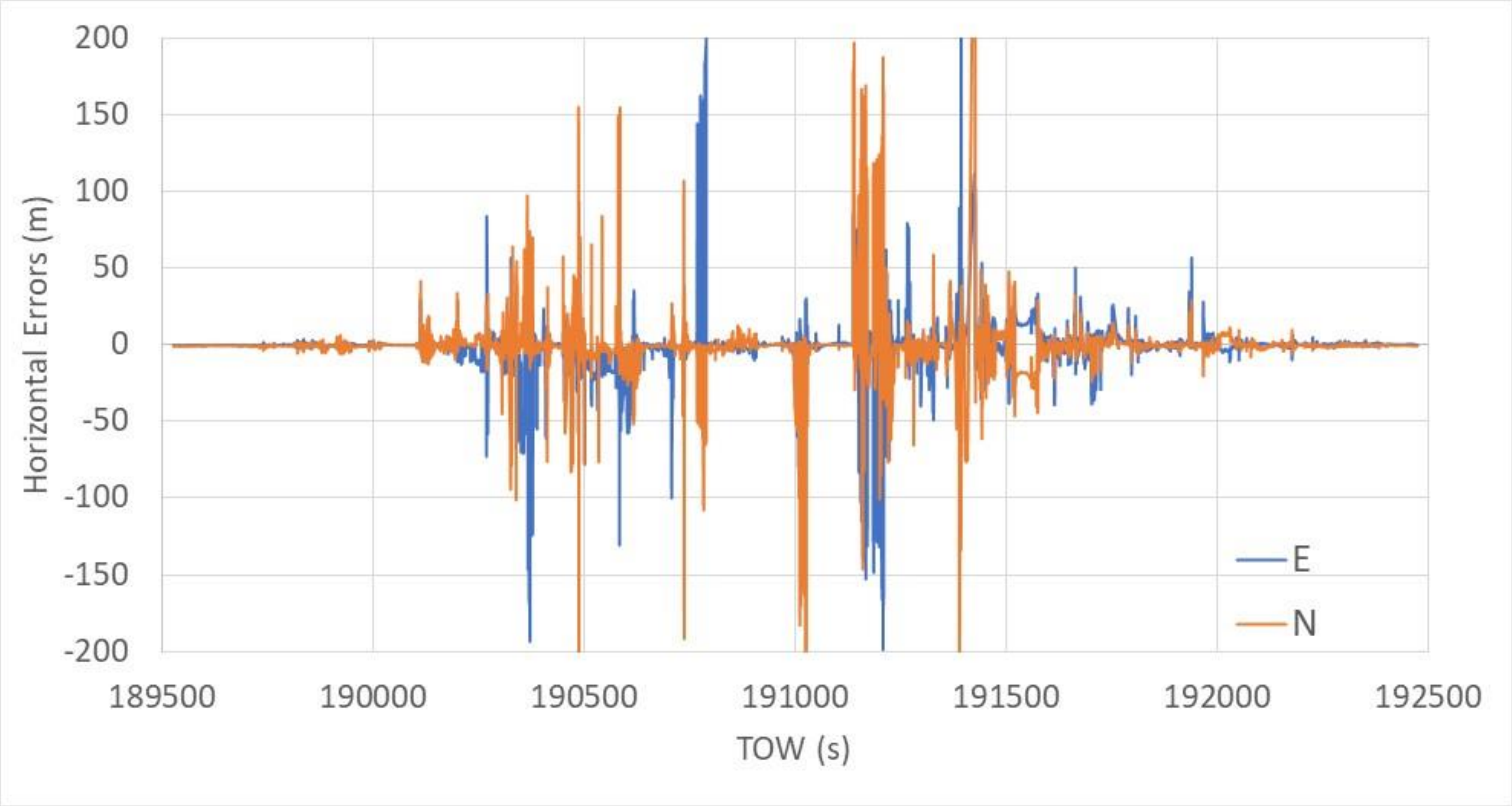


Test route (TUMSAT-MARUNOUCHI-GINZA-TUMSAT)

- Day : 2022/5/31
- Time : 04:38 - 05:31 (UTC)
- Receiver : u-blox F9P (base and rover), 5Hz
- IMU : ST (Acc. 3 axes, Gyro 3 axes), 50Hz
- Odometer : Over 1000 pulses from the car
- Car : SUBARU IMPREZA SPORT
- Reference : Post-processed POSLVX
- Base station : TUMSAT

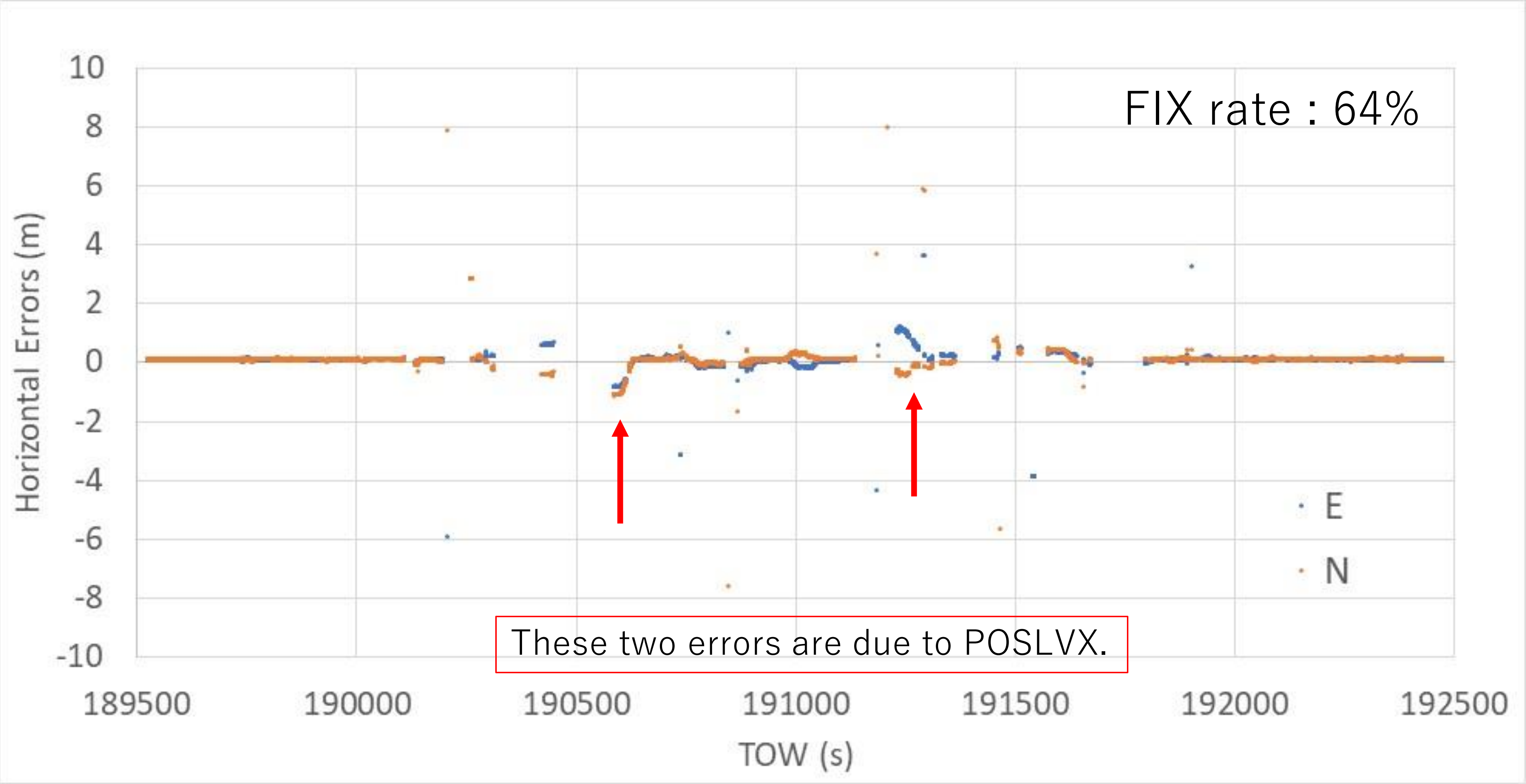


DGNSS



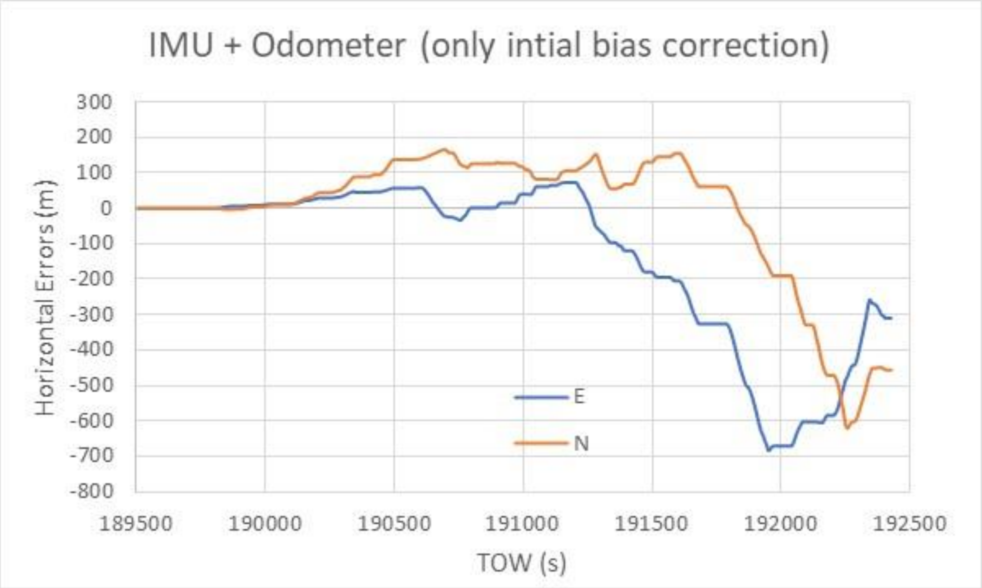
Horizontal Errors (m)
200
150
100
50
0
-50
-100
-150
-200
189500
190000
190500
191000
191500
192000
192500
TOW (s)
E
N

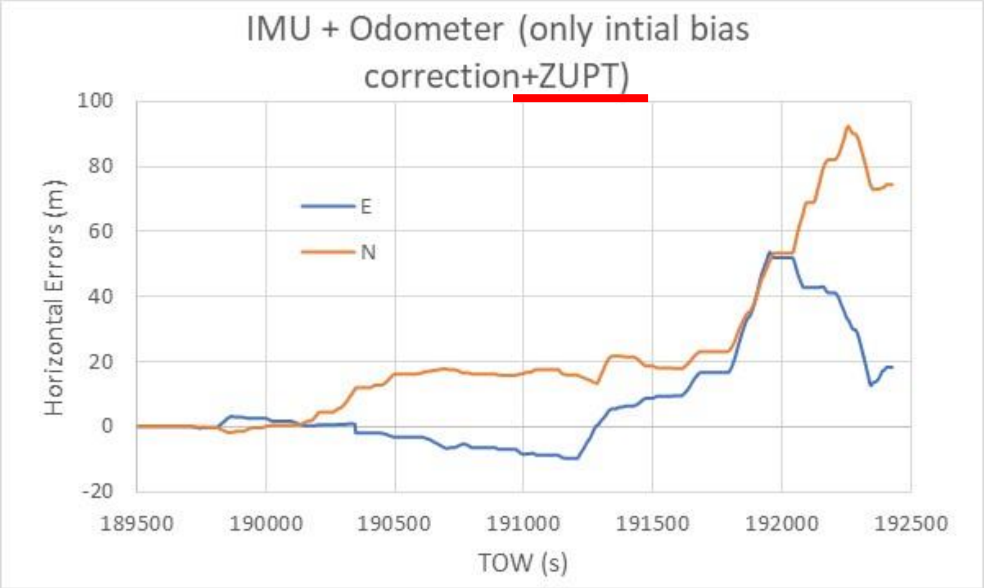
RTK-GNSS



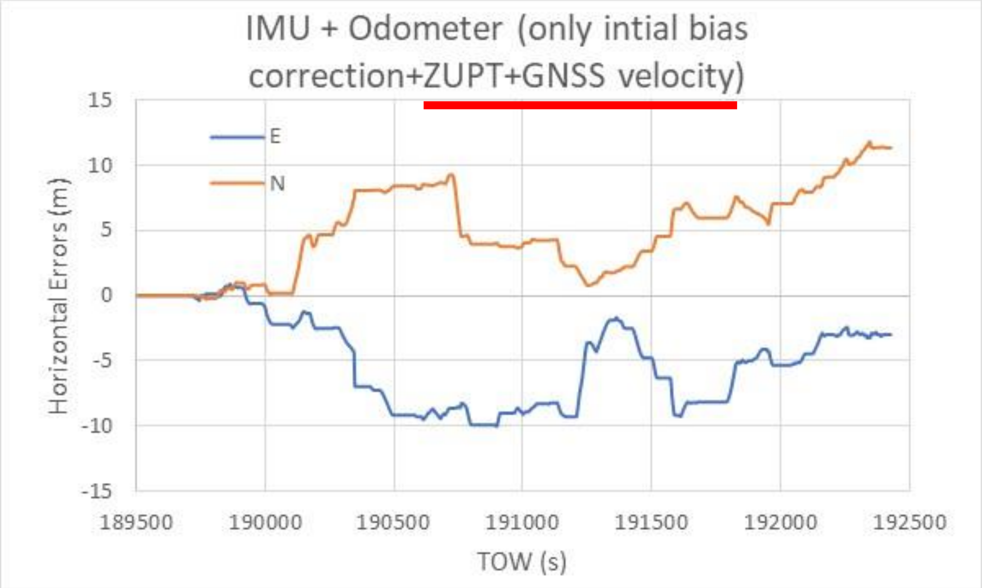
FIX rate : 64%
Horizontal Errors (m)
10
8
6
4
2
0
-2
-4
-6
-8
-10
189500
190000
190500
191000
191500
192000
192500
TOW (s)
E
N
These two errors are due to POSLVX.

IMU + Odometer + GNSS based velocity
-no absolute position-



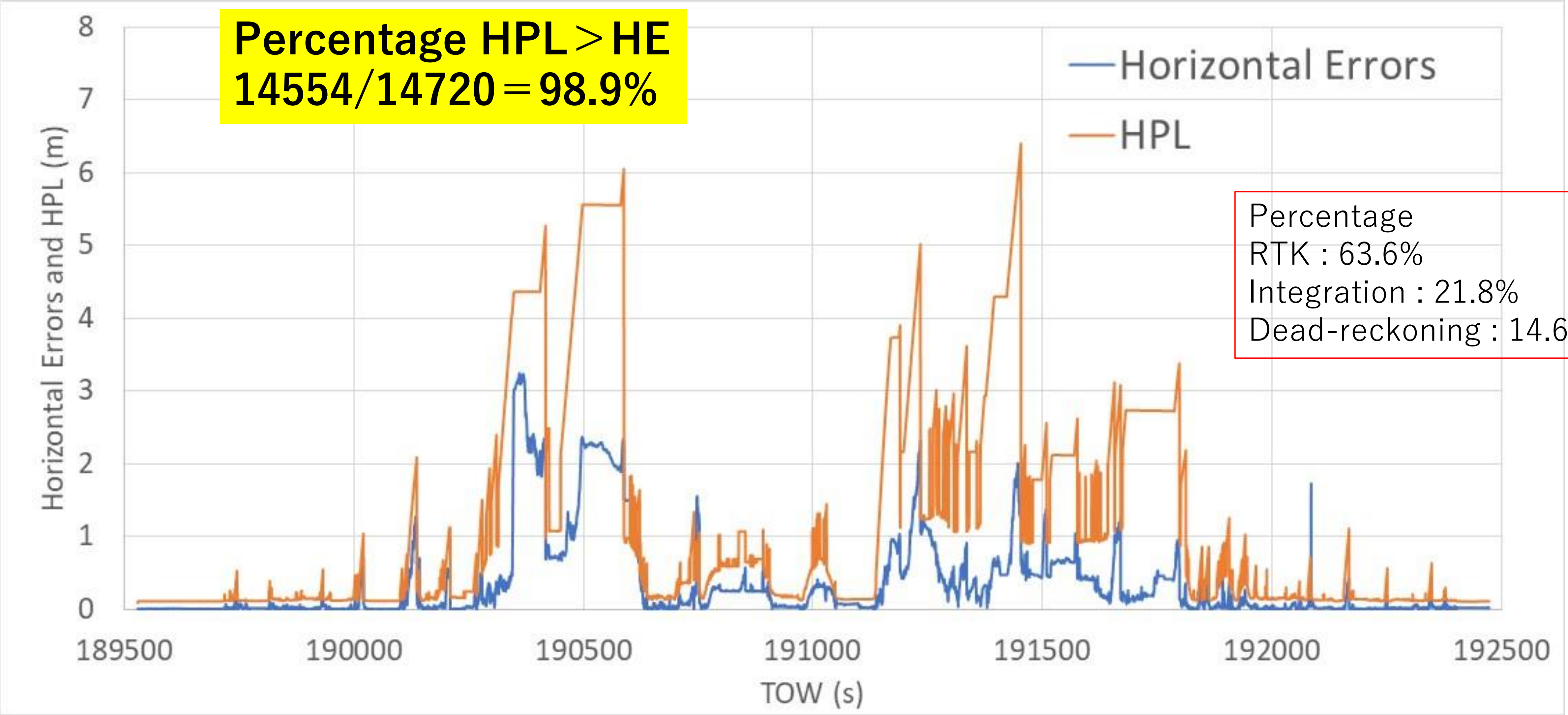


Initial position is set RTK position.



Proposed HPL

Percentage HPL＞HE
14554/14720＝98.9%



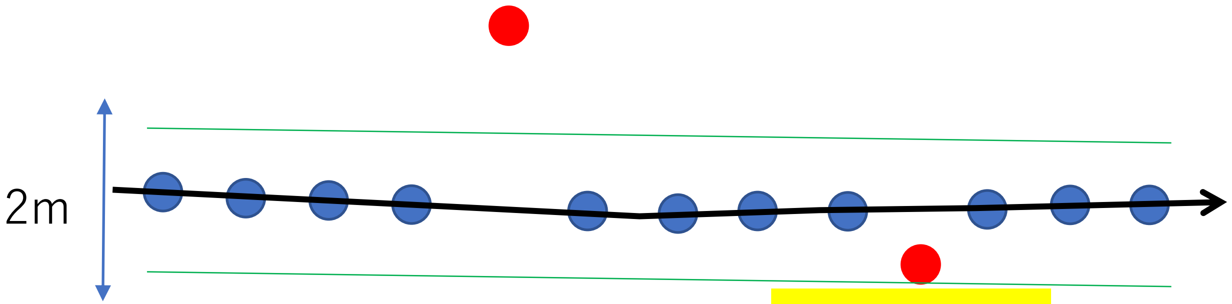
Percentage
RTK : 63.6%
Integration : 21.8%
Dead-reckoning : 14.6%

Summary

- Commercial product provide reasonable HPL using GNSS/IMU/Odometer.
- Lab's software also provide HPL, but we still need to improve it.
- Under open sky condition, PL will work well.
- PL using only GNSS is not reliable especially in challenging environment.
- Adding IMU/Odometer compensates a lot for the above weaknesses.
- Difficult to use FLOAT/DGNSS positions (absolute position as well as PL).
- Adaptive KF will compensate it by weighting the predicted position.
- Odometer is not always available. For example, under snow condition.

Two Challenges (remaining issues)

How to treat wrong RTK Fixes

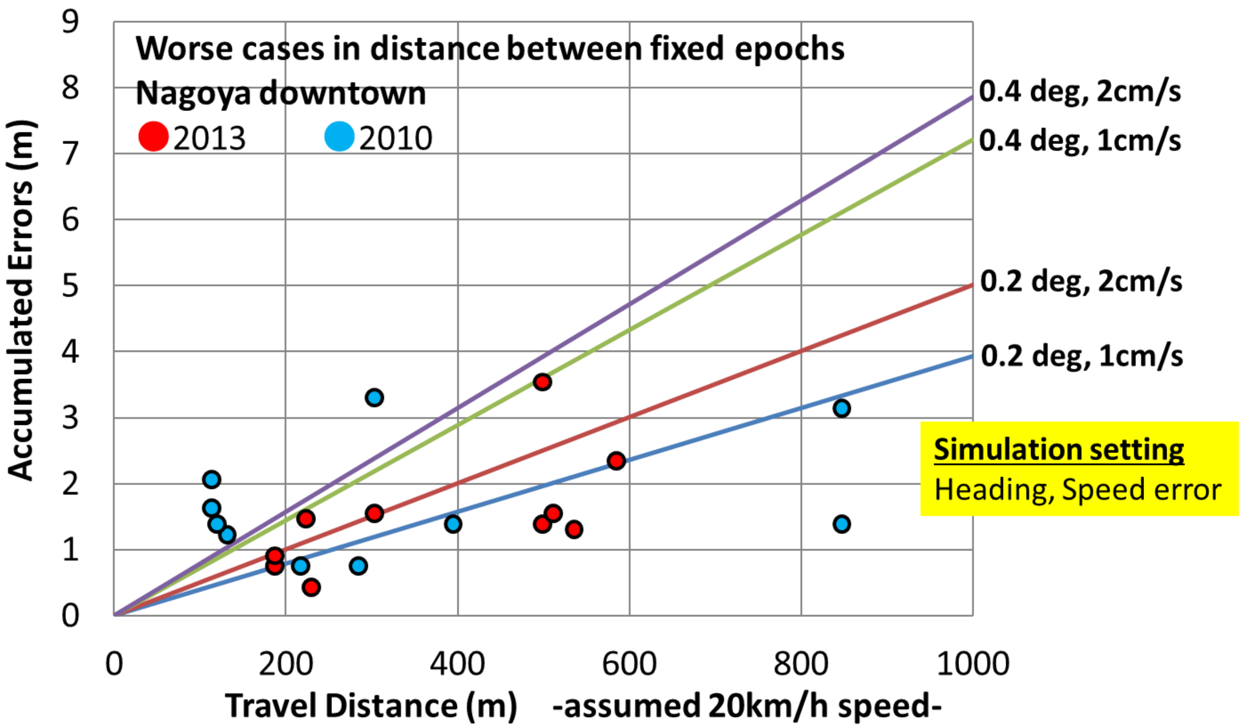


1. GNSS/IMU/Speed integrated position assures 2-3 meters. It is possible to detect large errors of the wrong fixes. However, it will be difficult to detect small errors.

2. Multi-antenna approach (GNSS compass)

3. More reliable ambiguity search (->low fix rate)

Heading accuracy in dead reckoning



At present, RTK-GNSS is better than 2010,2013. Furthermore, low-cost nice receiver is available. **The accuracy of low-cost IMU is still challenging.**