Tokyo University of Marine Science and Technology

Laboratory of Satellite Navigation Engineering

Performance Analysis of Loosely Coupled RTK-GNSS/IMU/Vehicle Speed Sensors in Urban Environment

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Background

- Recently, advanced driver assistance systems with features such as lane change assist and automatic braking in automotive applications have experienced a rapid growth.
- For a more advanced operating system implementation, improvement of the vehicle location accuracy is desired. Positioning by GNSS is becoming a widely used method for this purpose where accurate positioning at a few cm-level can be obtained by using Real-Time Kinematic (RTK) technique.

Background

- the use of RTK-GNSS
  - For precise survey
  - For mapping

- What's the performance of the RTK-GNSS in urban environments?
- The possibility of accuracy improvement technique using integrating GNSS and vehicle sensors.

Objective

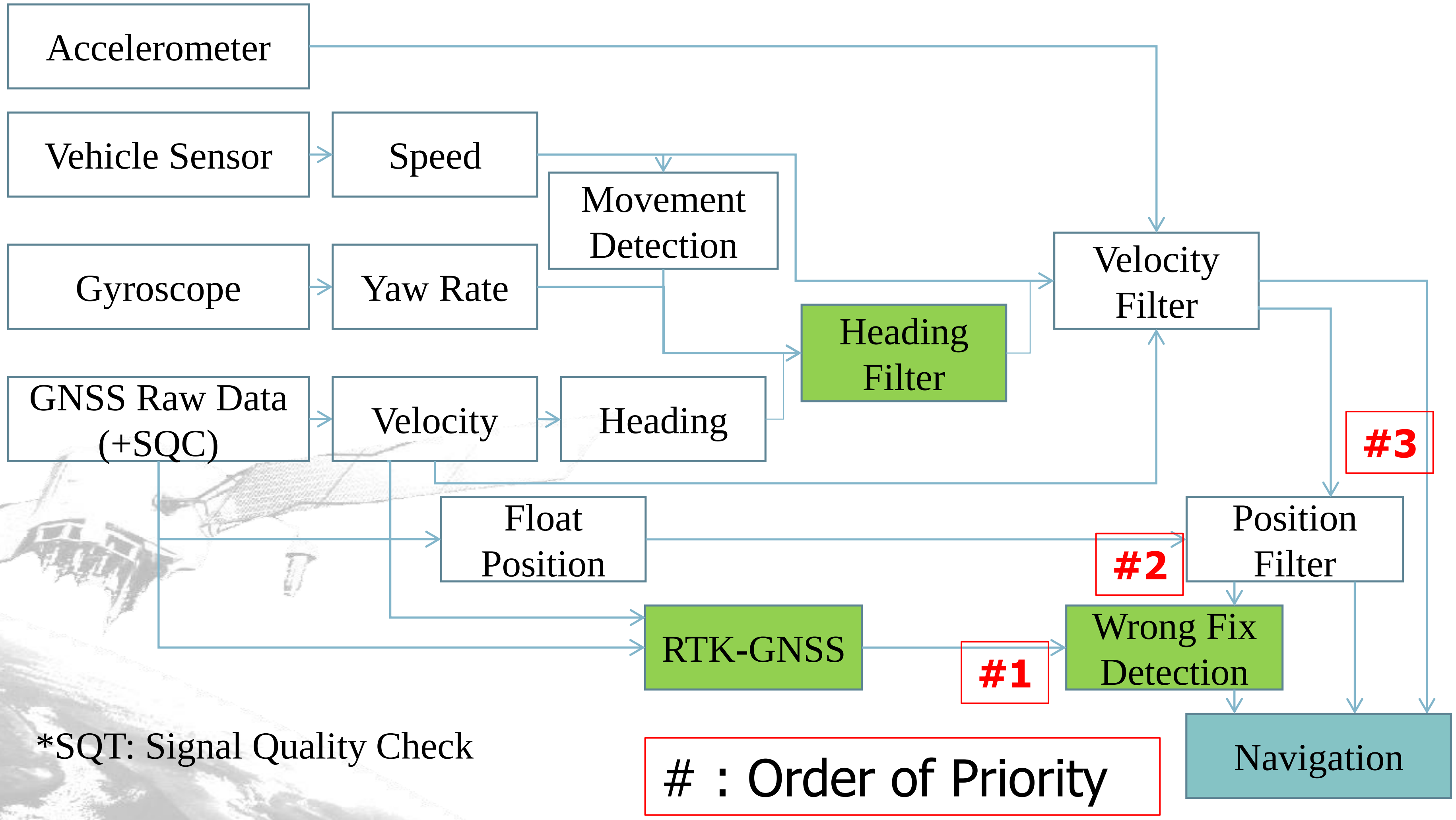
The position measurement with large errors over several meters can not be avoided

Multipath, DOP, and wrong FIX etc. | GNSS signal outage

1. How to integrate the RTK-GNSS, IMU, and vehicle sensors in an effective way
2. What benefits the integration will yield

TARGET: Maximum horizontal error < 1.5m

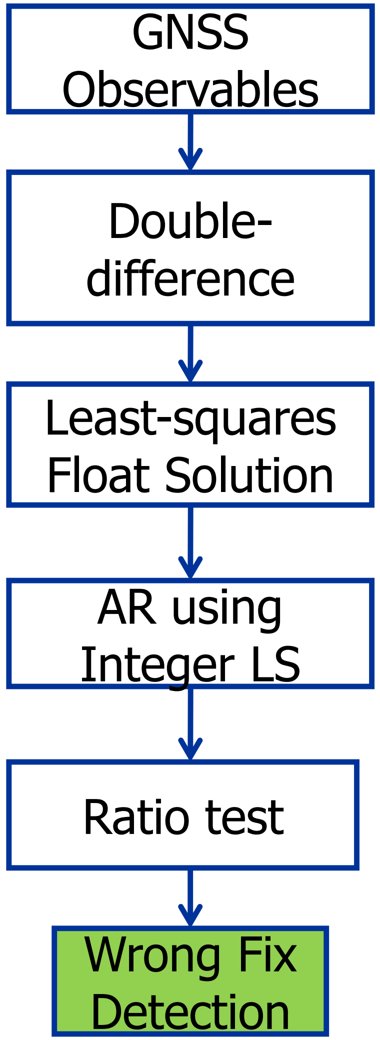
Algorithm of Integration



*SQT: Signal Quality Check

Position from RTK-GNSS

- Double-differenced observations in each satellite system → **GPS/QZS+BDS**
- Signal quality check and ADOP
- Doppler aided LAMBDA method
- Ratio Test



Position from RTK-GNSS

- Ambiguity Resolution
  - LAMBDA method
    - used to resolve Integer ambiguities
    - the ambiguities are resolved in a single epoch
  - Ratio Test
    - used to validate that the resulting ambiguities are correct
    - the threshold for the ratio test is set 3

- The value of Ratio test ≥ 3 Fix solution

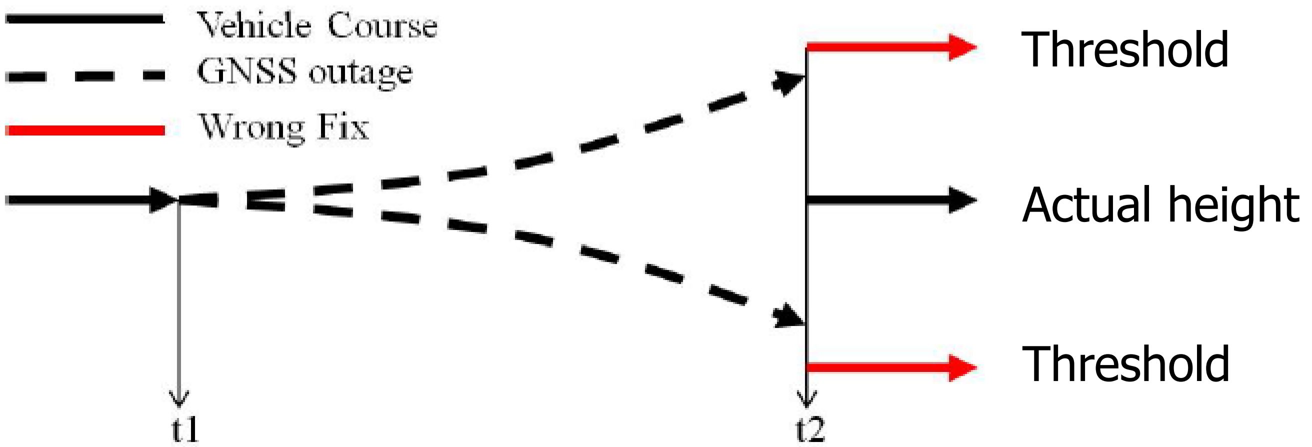
Wrong FIX Detection

- Calculate the change of the altitude

$$\Delta h = \int_{t1}^{t2} v \sin(\theta) dt$$

Wrong Fix ⟶ Over 1m

- θ is the pitch angle change deduced from a pitch rate gyro
- Epochs of t1 and t2 are only used when the RTK-GNSS is available



Velocity from GNSS

- Relative velocity → Doppler shift (Doppler frequency)
- Ephemeris information → satellite velocity
- Velocity of the vehicle can be calculated as follows

$$\Delta f = \frac{f\rho'}{c}$$

$$(V_i - V)S_i + \Delta\rho = \rho_i$$

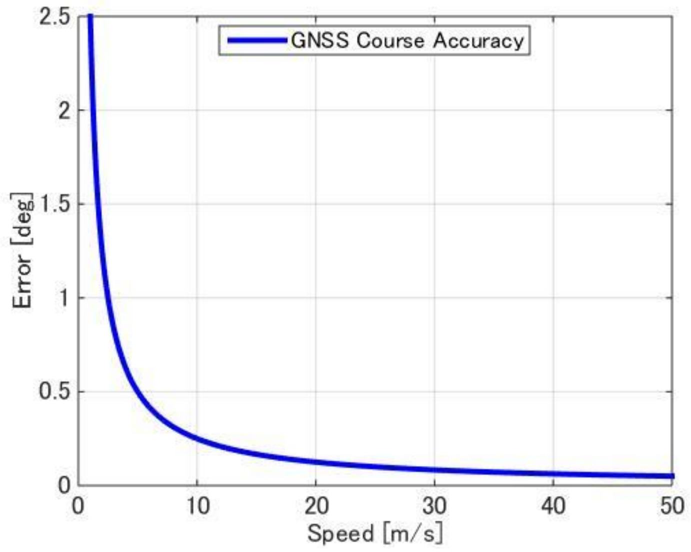
- f :the frequency of the carrier from GPS
- Δf :the frequency shift from the Doppler measurement
- c :the speed of light
- ρ' :the relative speed between the satellite and the vehicle
- V_i :the velocity of the satellite
- V :the velocity of the vehicle
- S_i :the eye vector of the satellite
- $\Delta\rho'$:the error of the oscillator

$$E_t = E_{t-1} + \frac{\left(V_{E_{t-1}} + V_{E_t}\right)}{2}\Delta t$$

$$N_t = N_{t-1} + \frac{\left(V_{N_{t-1}} + V_{N_t}\right)}{2}\Delta t$$

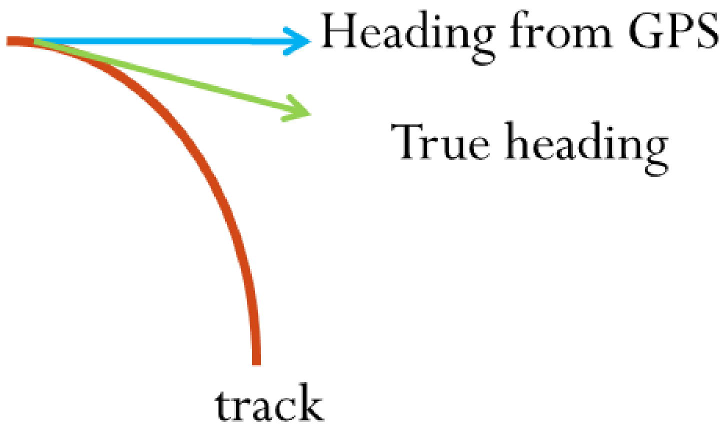
Heading from GNSS velocity

- We can not get the right heading when the vehicle is stationary or in a low speed
  - GNSS velocity measurement has a few cm/s noise



- The heading error will increase when the vehicle is moving in a high yaw rate
  - GNSS sampling is in a low rate

- The data not satisfies the speed threshold or the DOP threshold will not be used



Heading Estimation Algorithm

ψ_{G_k}:GNSS heading ω_{g_k}:Angular velocity (IMU)

- Moving situations HDOP threshold : 2.5
  - Low speed (below 0.5 m/s) (from vehicle speed sensors)
  - Normal speed (over 0.5 m/s) with low yaw rate (below 4°/s)
  - Normal speed with high yaw rate (over 4°/s)

- The measurement covariance will be updated in each state.

$$x_k = (\psi_{G_k}, \omega_{g_k})$$

$$x_{k+1} = F_k x_k + G w_k$$
$$y_k = H x_k + v_k$$
$$F = \begin{bmatrix} 1 & \Delta t \\ 0 & 1 \end{bmatrix}$$

$$\hat{x}_{k|k} = \hat{x}_{k|k-1} + K_k(y_k - H_k \hat{x}_{k|k-1})$$

$$\hat{x}_{k+1|k} = F_k \hat{x}_{k|k}$$

$$K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1}$$

$$P_{k|k} = P_{k|k-1} - K_k H_k P_{k|k-1}$$

$$P_{k+1|k} = F_k P_{k|k} F_k^T + G_k Q_k G_k^T$$

$$R = \begin{bmatrix} \sigma_{\Psi_G}^2 & 0 \\ 0 & \sigma_{\Psi_g}^2 \end{bmatrix}$$

DR(Estimated heading + Speed Sensors)

$$E_t = E_{t-1} + \frac{(\cos(\theta_{t-1})\ V_{t-1} + \cos(\theta_t)\ V_t)}{2} \Delta t$$

$$N_t = N_{t-1} + \frac{(\sin(\theta_{t-1})\ V_{t-1} + \sin(\theta_t)\ V_t)}{2} \Delta t$$

Experiment

GNSS Antenna	NovAtel 703 GGG
GNSS Receiver	Trimble SPS 855
Baseline Length	- 10km
IMU	Analog Devices ADIS16445
Speed Sensor	Standard Vehicle Loaded Wheel Speed Sensors
Reference	POS/LV (Applanix) positional accuracy within 30 cm
Location	Nagoya City, Japan **(dense urban areas)**

Experiment Course

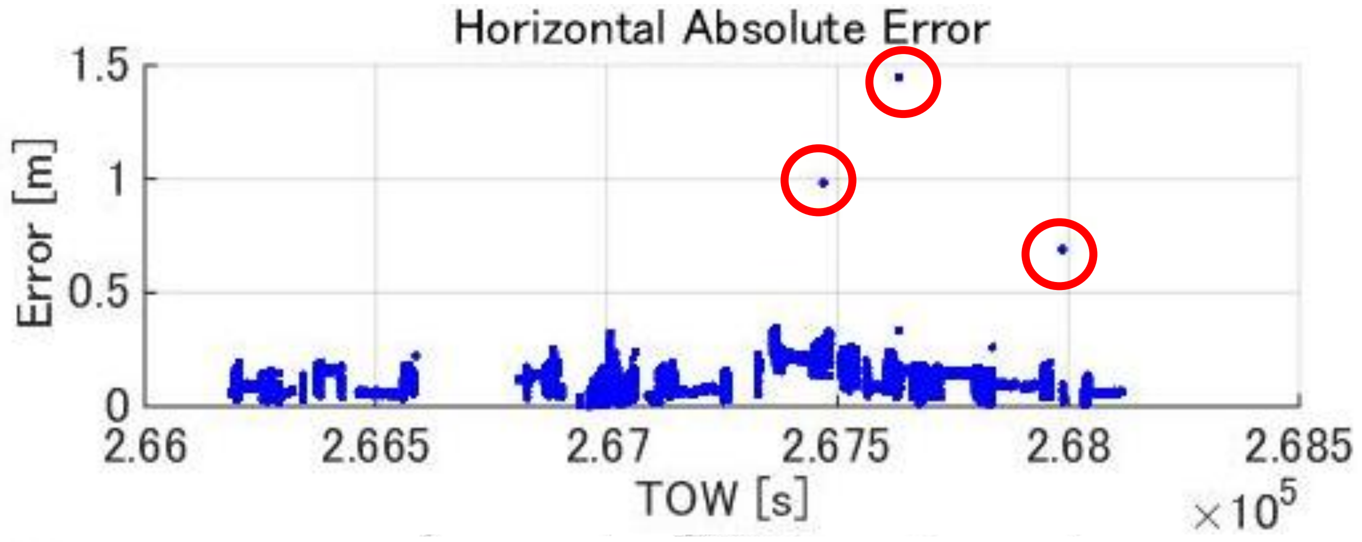
Total 3 tests
Period : about 30min
Data rate : 10Hz

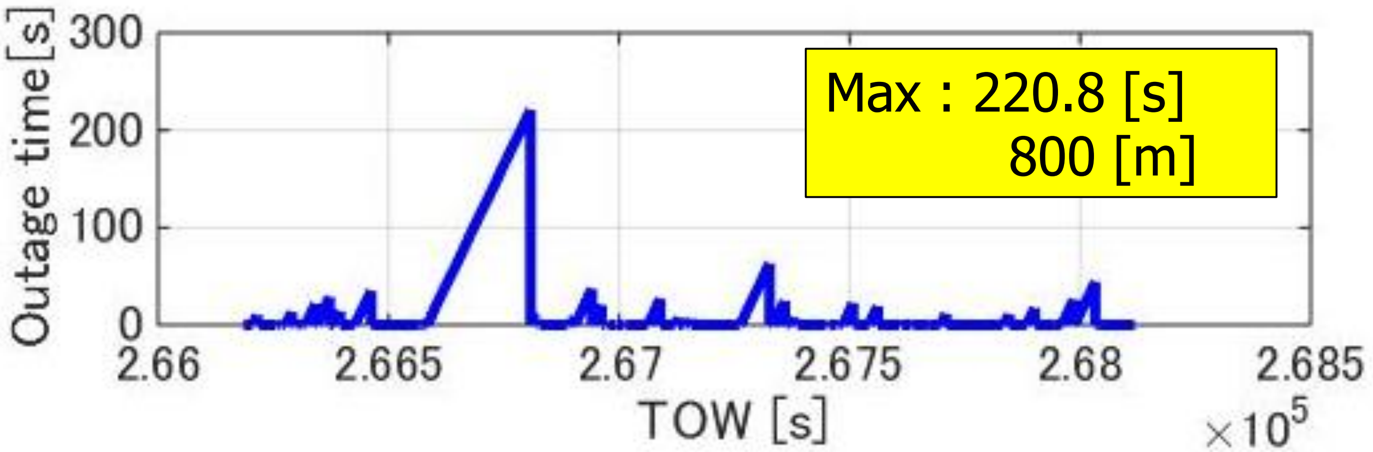
Test	NUS (ave.)
1	9.2
2	9.7
3	9.3

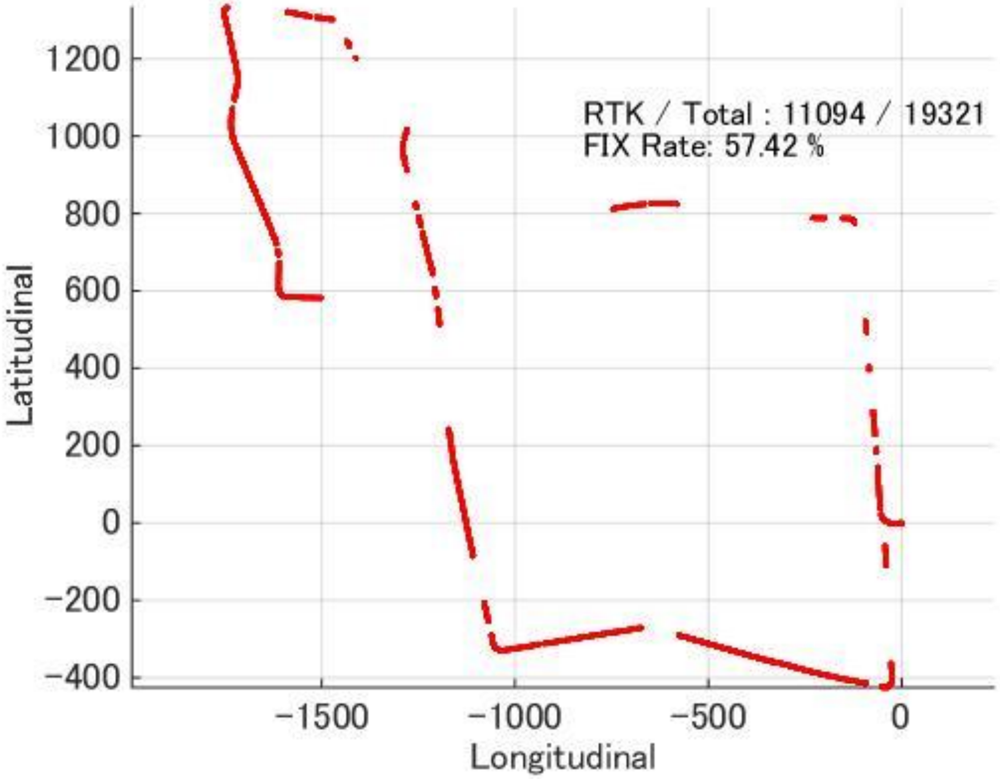
Number of used satellites.

●Trajectory ●Under pass

RTK-GNSS Performance

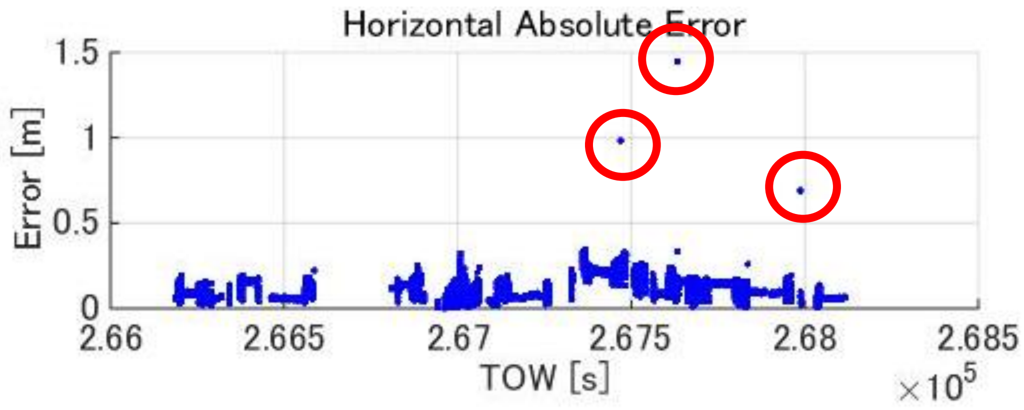


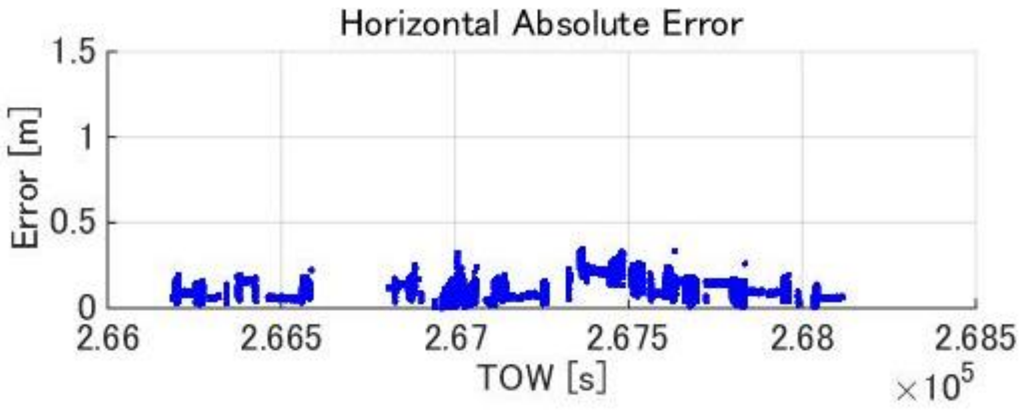


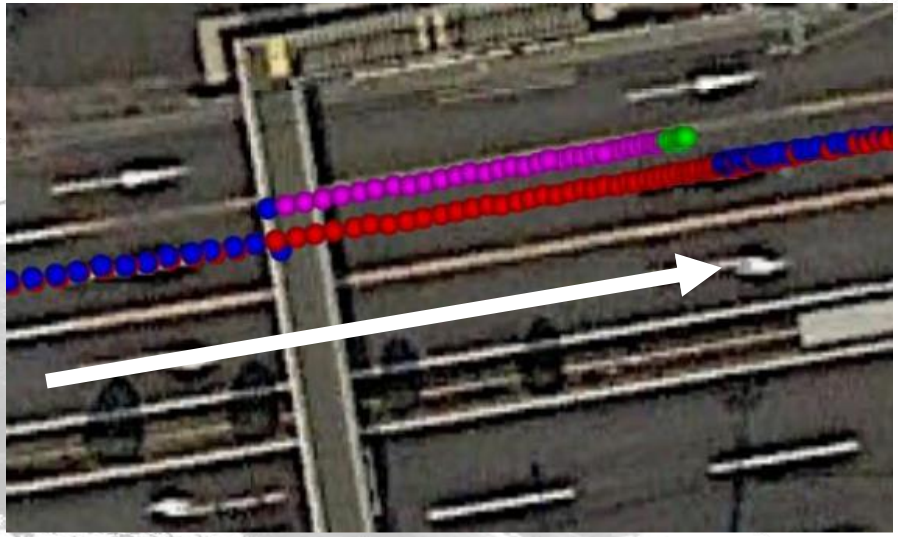


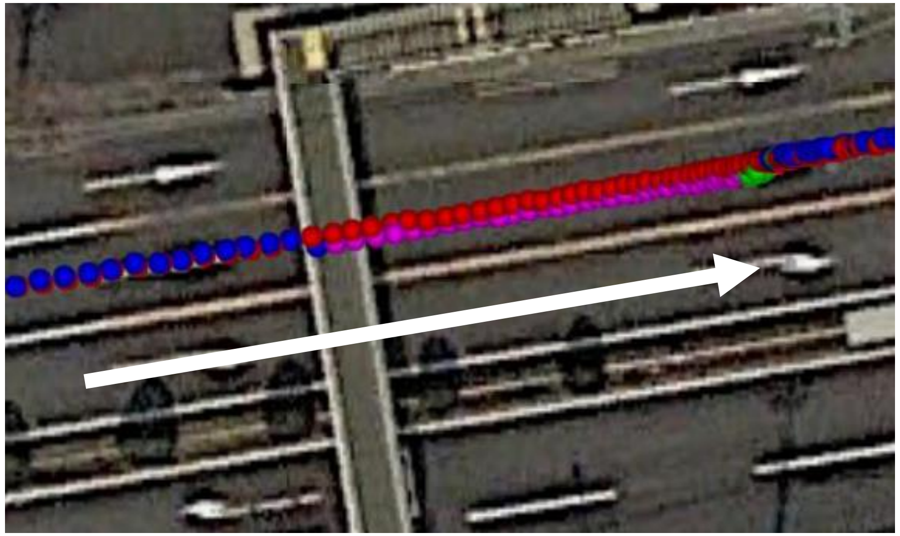
+QZS and BDS increased the availability a lot.
About 1.5-2 times compared with only GPS

Wrong FIX Detection Results





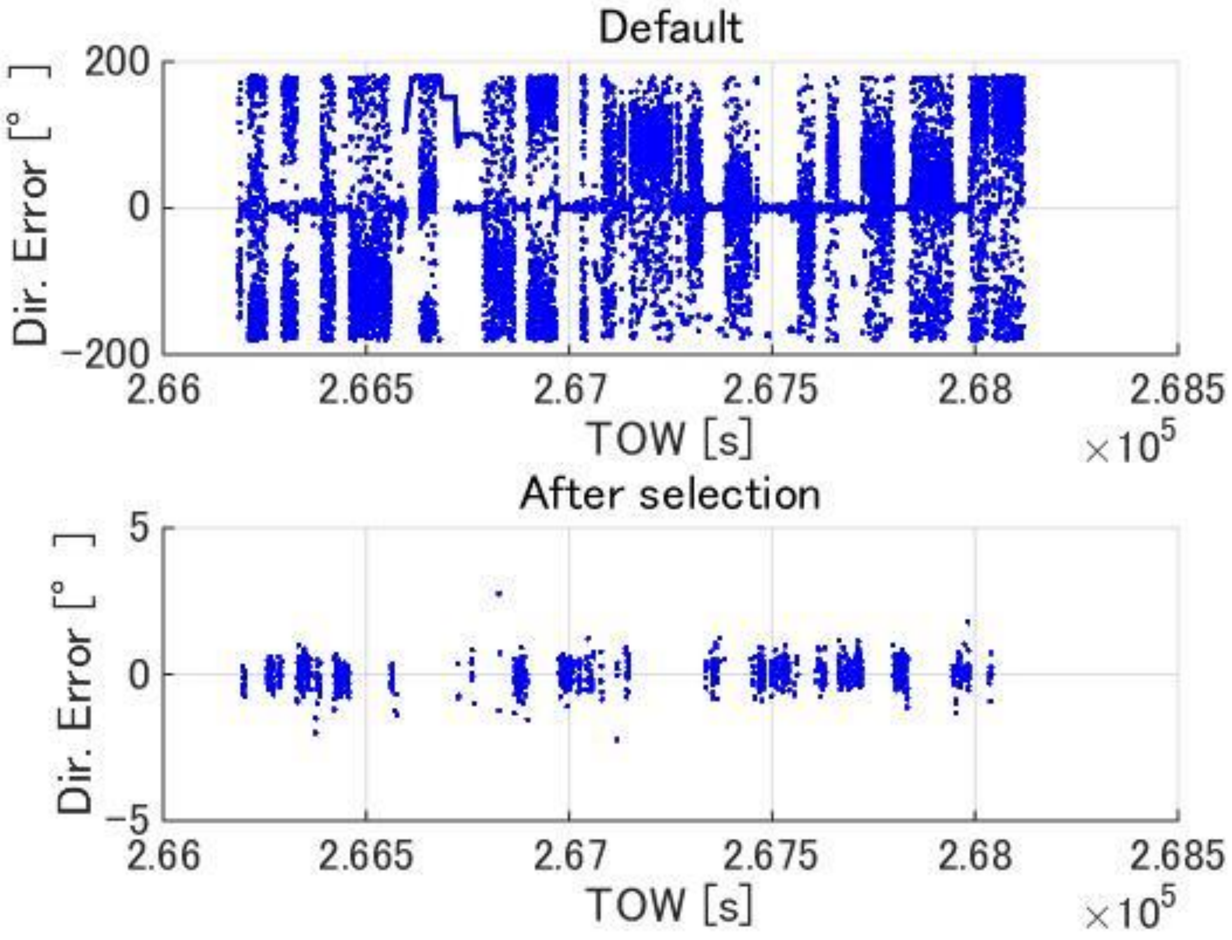


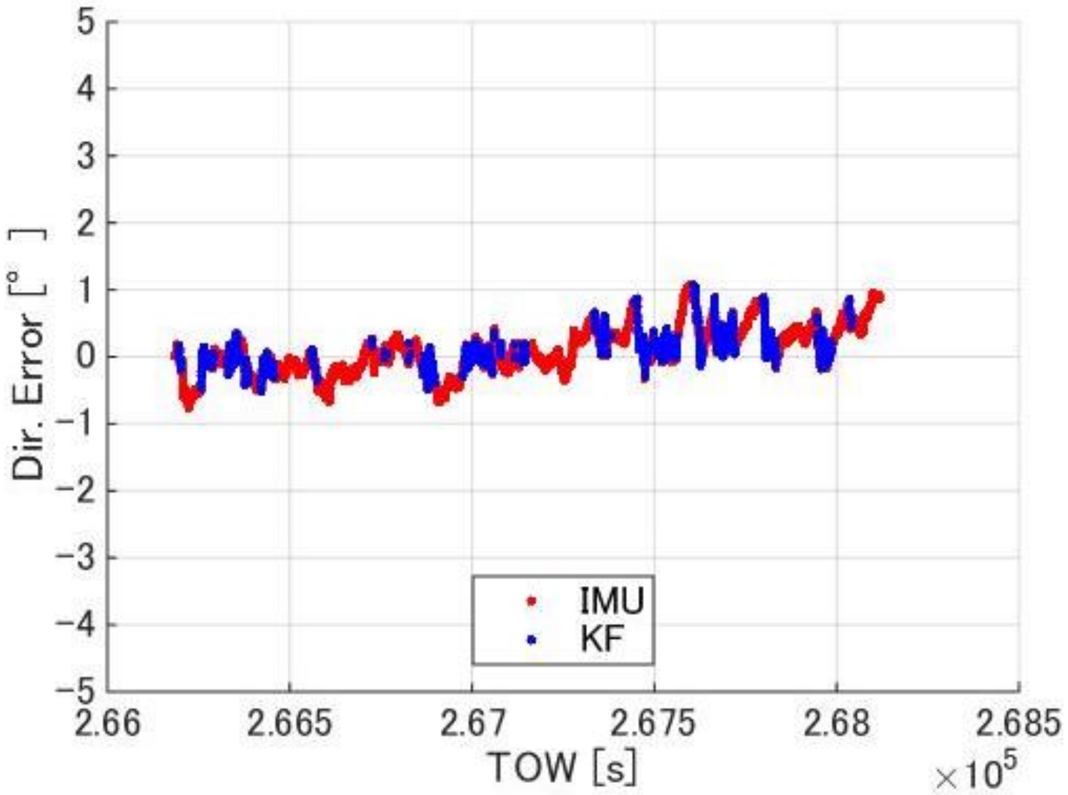


●Reference ●RTK. ●GNSS Vel. ●IMU

Google earth

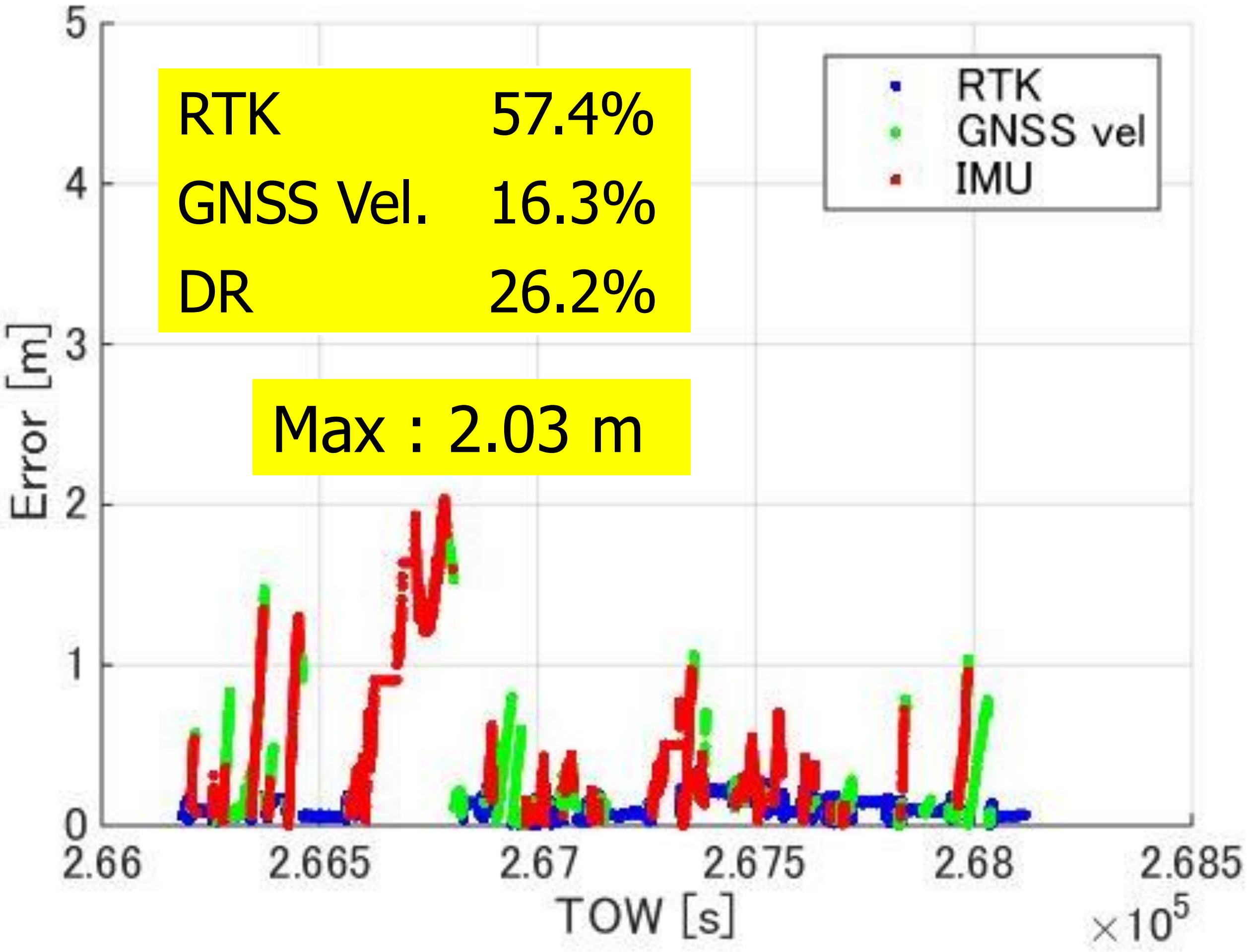
Results of the Proposed Heading Estimation

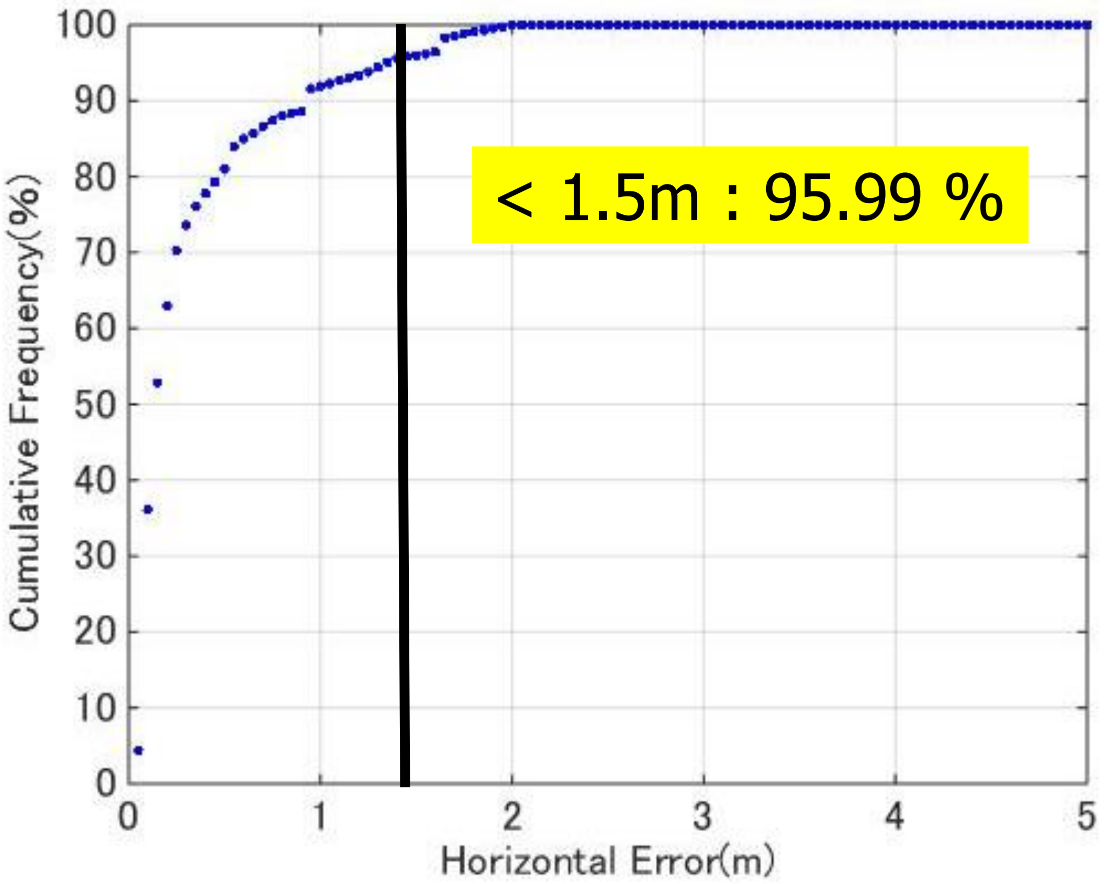




	Test1	Test2	Test3
Ave. [deg]	0.09	-0.18	-0.05
RMSE [deg]	0.35	0.45	0.37

Overall Results





Summary

- Loosely coupled integration (RTK-GNSS/IMU/Speed sensors) method was proposed.
  RTK-GNSS has been improved by using multi-GNSS constellation.
  Wrong FIX detection was proposed and validated.

- Good accuracy was maintained using a simple integration method.
  Loosely coupled KF was used to estimate important heading information.

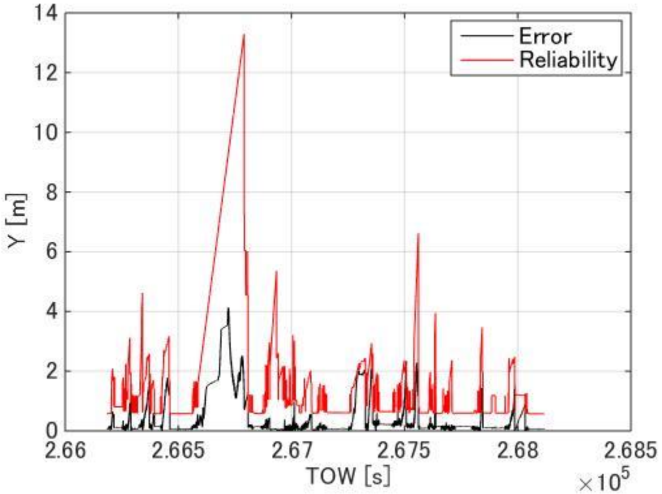
- Availability was improved to 100 %.
  Percentage within 1.5 m horizontal was 91 – 95 %.
  Maximum horizontal errors were reduced to 2 – 3 m.

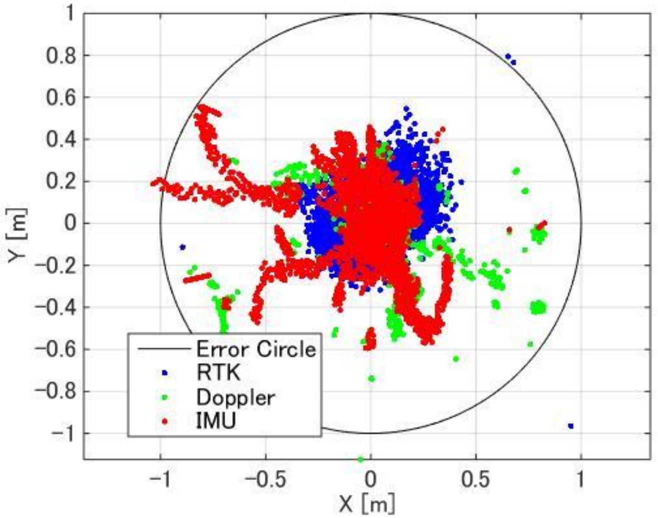
Test1		Test2		Test3	
<1.5m	Max	<1.5m	Max	<1.5m	Max
95.99 %	2.03 m	91.77 %	3.03 m	95.08 %	2.31 m

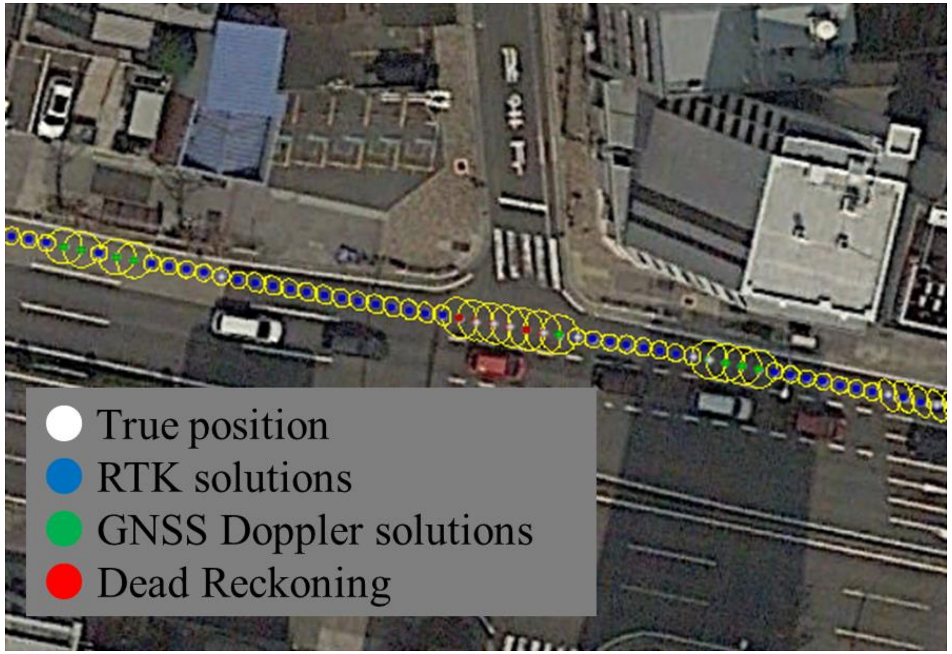
Future Work

- Integrity monitoring

  Positioning by GNSS relays on weak signals that have well-known vulnerabilities and when being integrated with other systems, integrity and performance-based monitoring becomes an important task for protection from faults in order to produce robust precise position estimation. It is also important to alert the user in case that the system can not reach the target performance.







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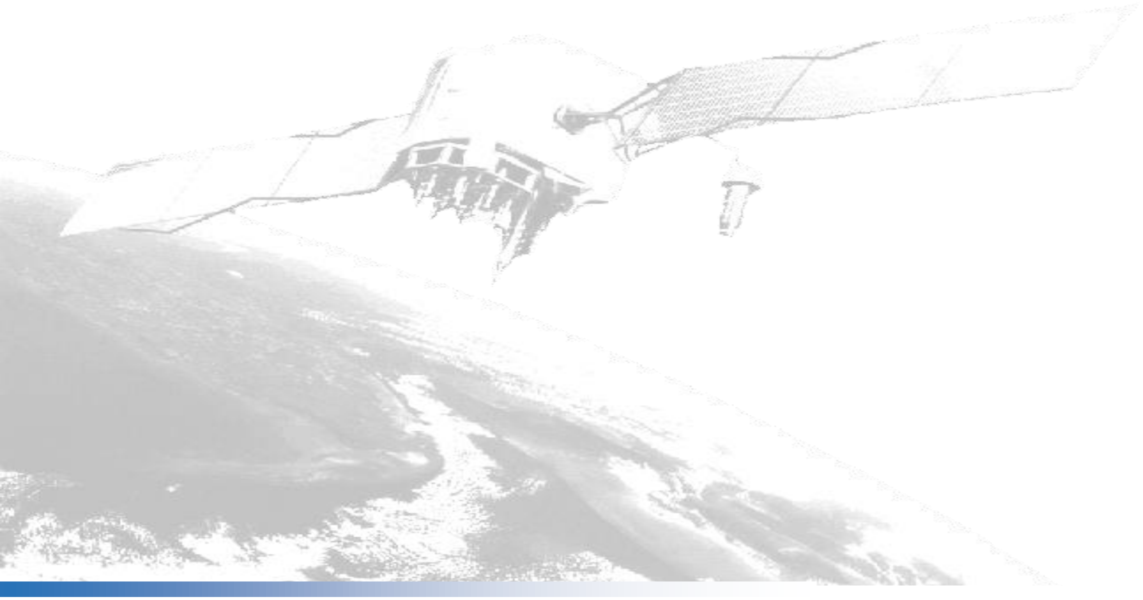
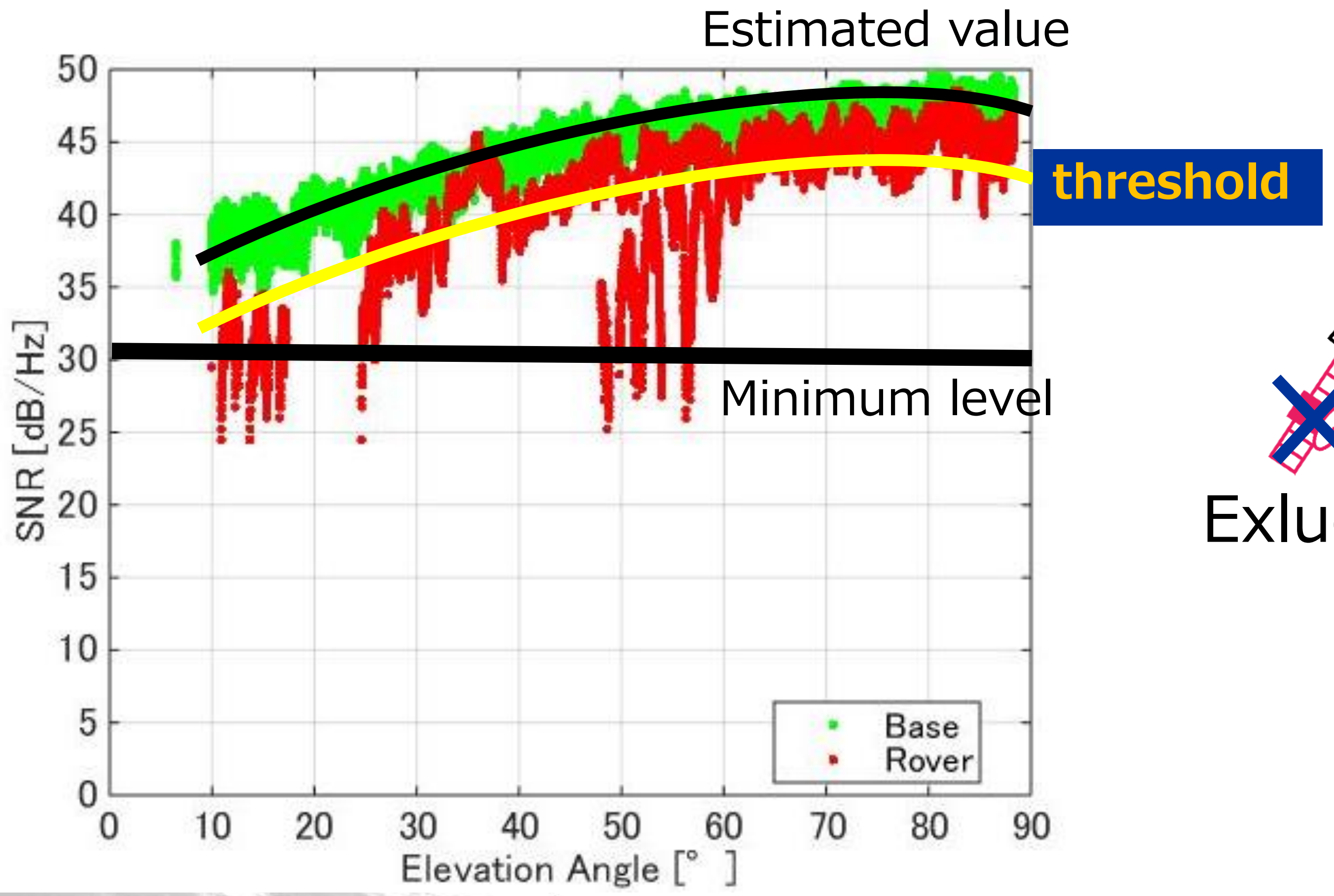
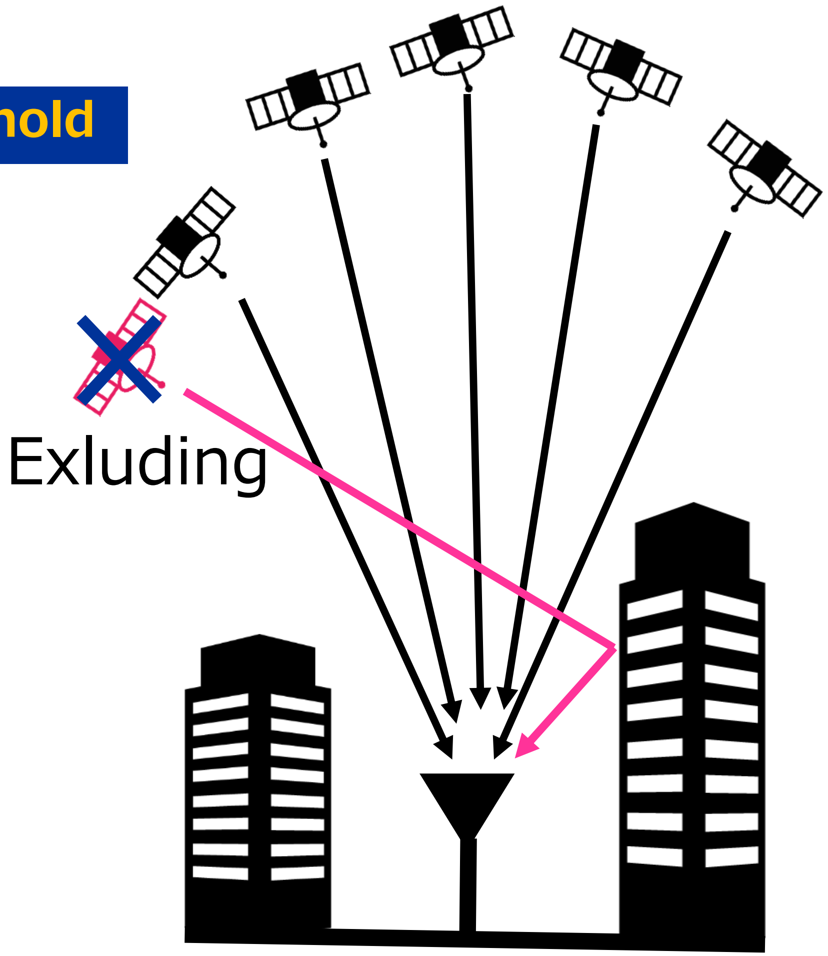


Signal Quality Test





Detect bad quality signal including multipath