Tokyo University of Marine Science and Technology

Laboratory of Satellite Navigation Engineering

Reliability Estimation for RTK-GNSS/IMU/Vehicle Speed Sensors in Urban Environment

Ren Kikuchi, Nobuaki Kubo (TUMSAT)

Shigeki Kawai, Ichiro Kato, Nobuyuki Taguchi (DENSO corporation)

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Contents

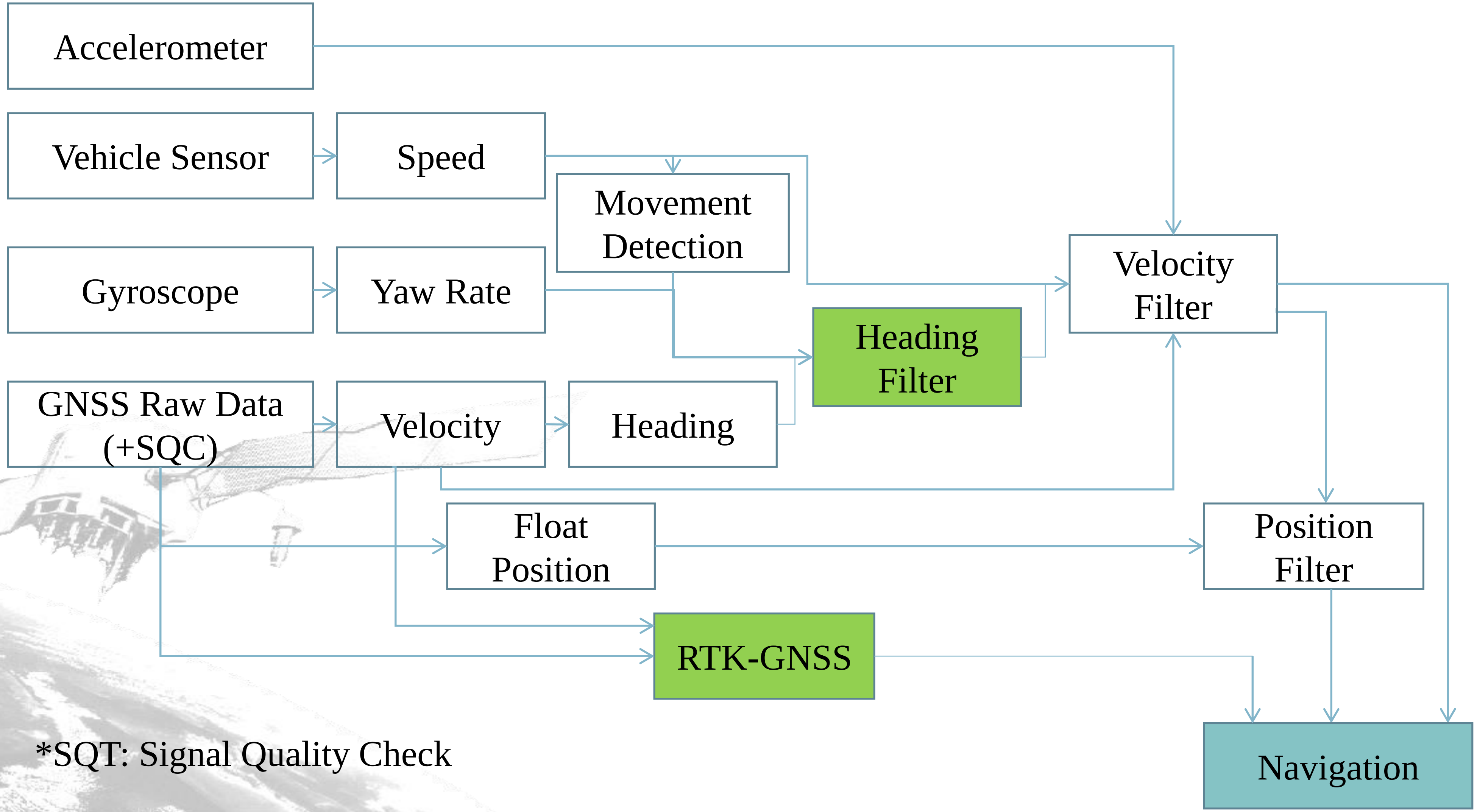
Background

- 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.
- Protection Level estimation

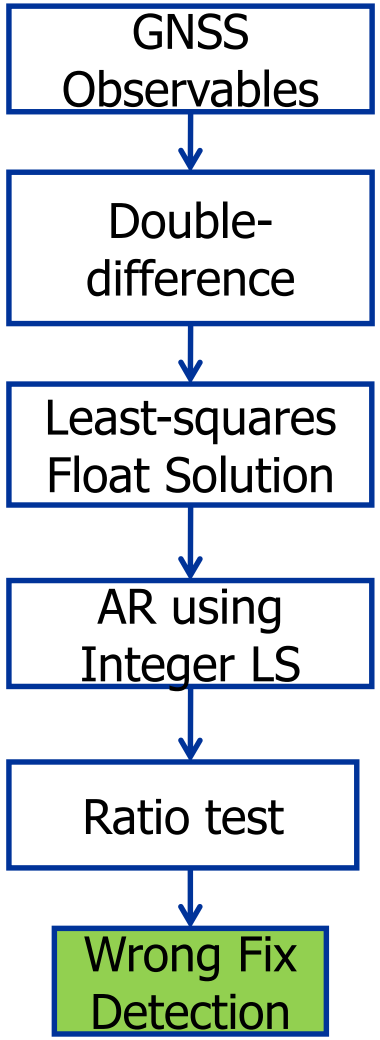
Algorithm of Integration



*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
  the ambiguities are resolved in a single epoch
- Ratio Test ≥ 3 Fix solution



Velocity from GNSS

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

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

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

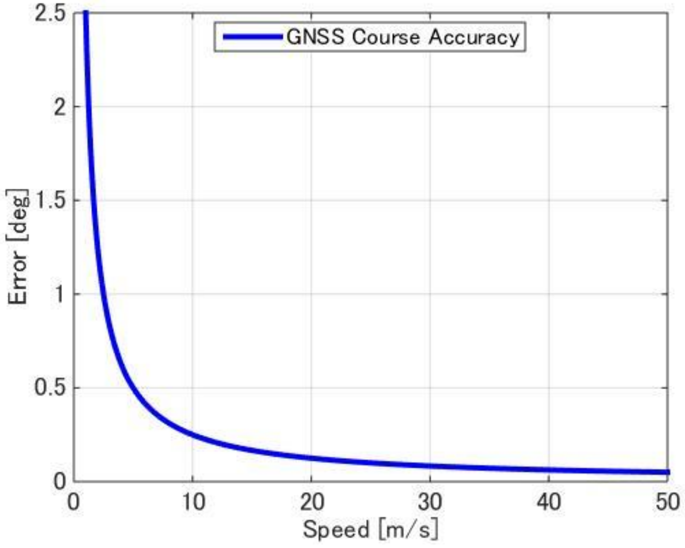
- f :the frequency of the carrier from GPS
- Δf :the frequency shift from the Doppler measurement
- c :the speed of light
- ρ' :the relative speed between the satellite and the vehicle
- V_i :the velocity of the satellite
- V :the velocity of the vehicle
- S_i :the eye vector of the satellite
- $\Delta\rho'$:the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

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

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

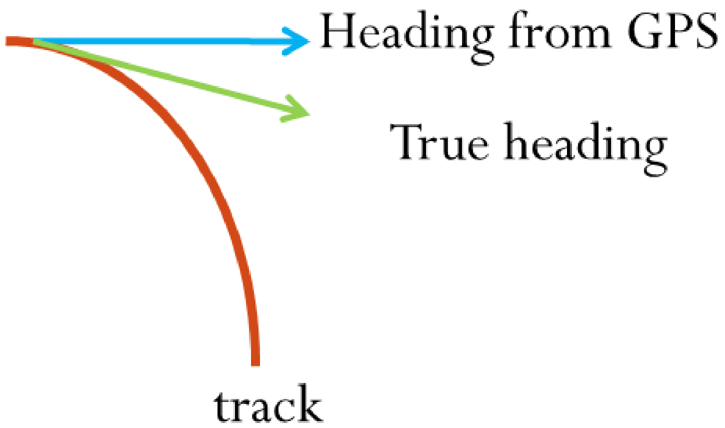
Heading from GNSS velocity

- 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.

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

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

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

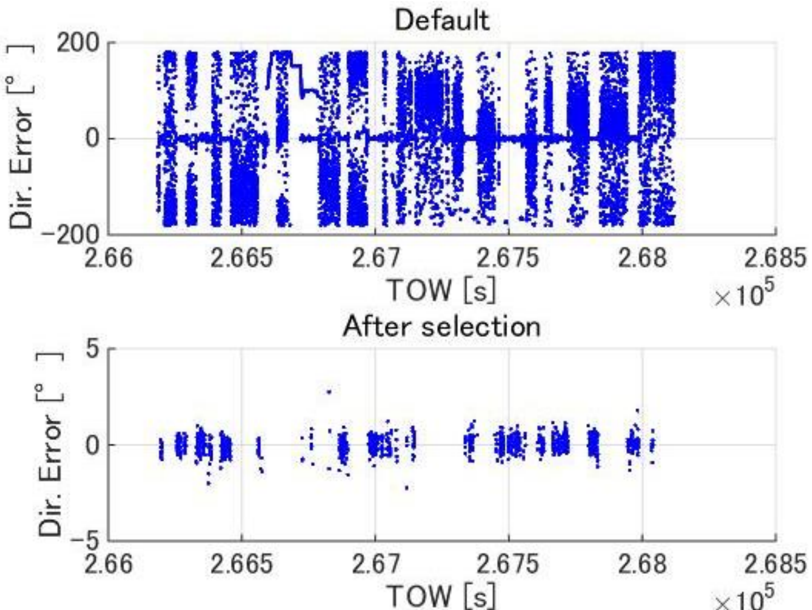
$$\hat{x}_{k+1|k} = F_k \hat{x}_{k|k}$$

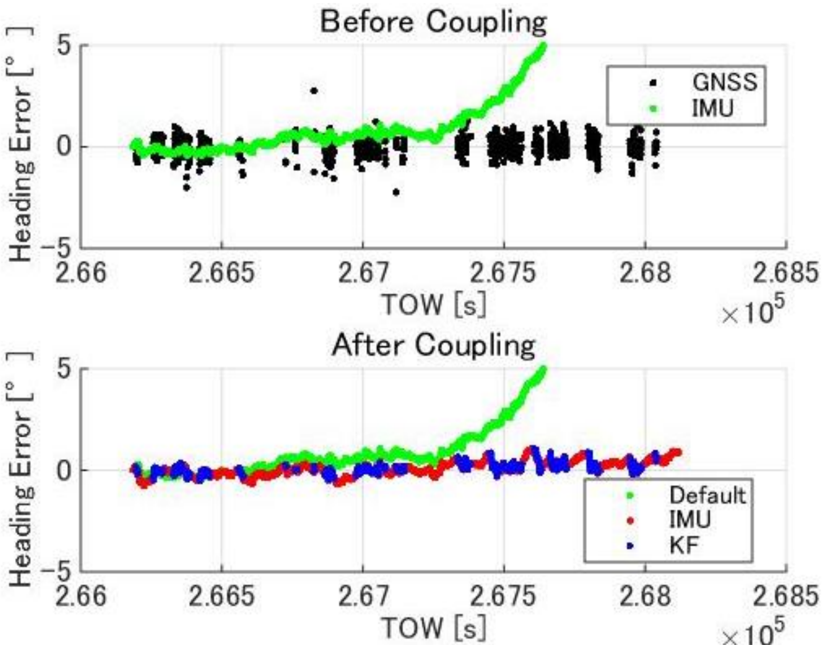
$$K_k = P_{k|k-1} H_k^T (H_k P_{k|k-1} H_k^T + R_k)^{-1}$$

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

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

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





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

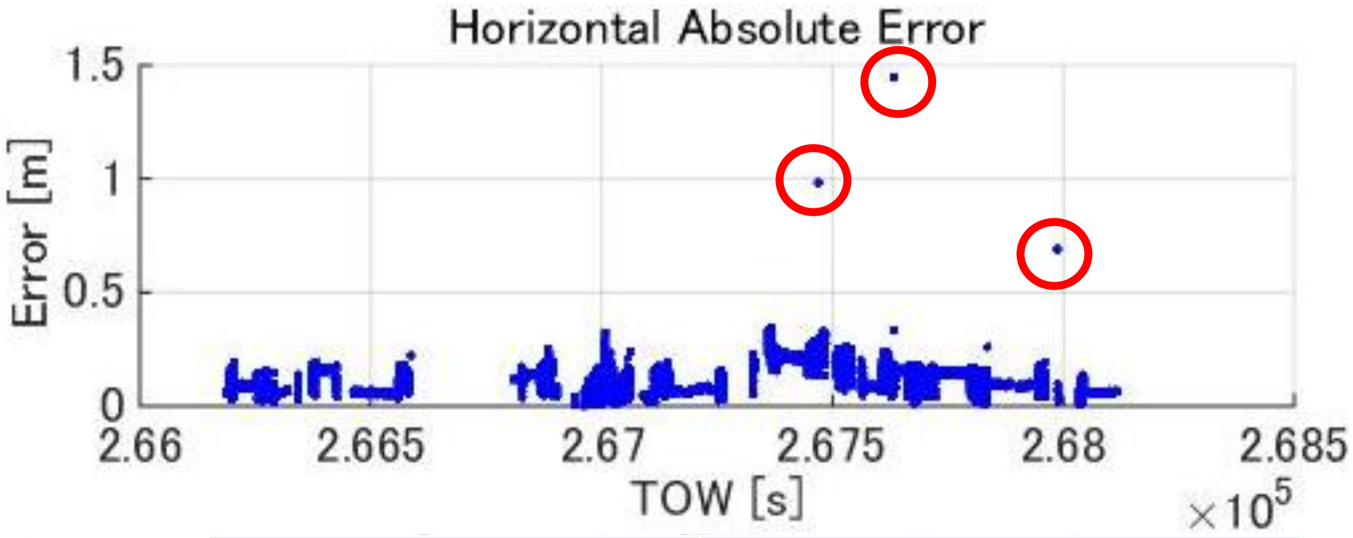
Total 3 tests
Period : about 30min
Data rate : 10Hz

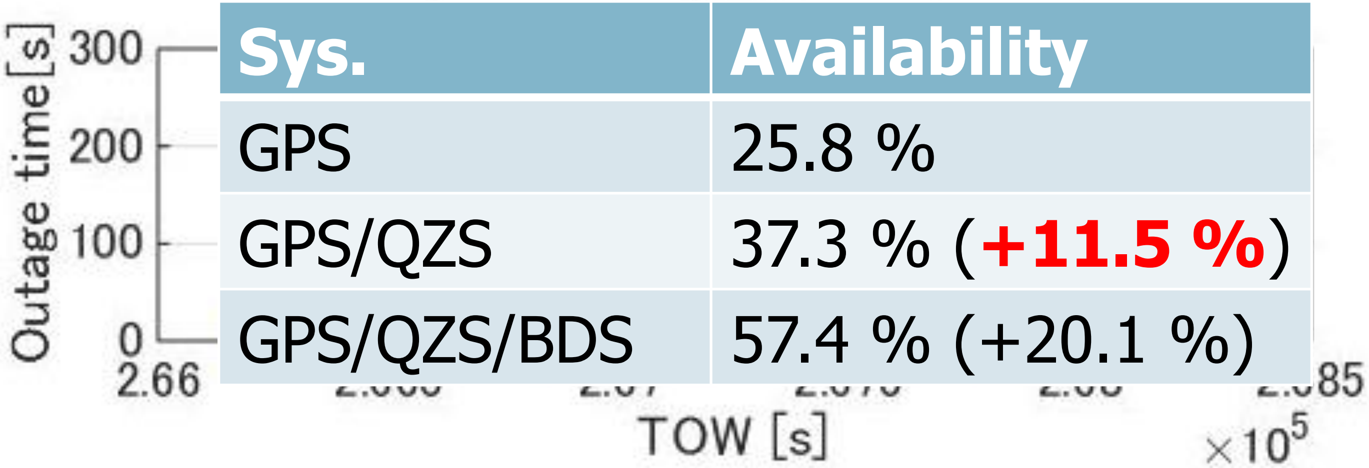
Test	NUS (ave.)
1	9.2
2	9.7
3	9.3

Number of used satellites.

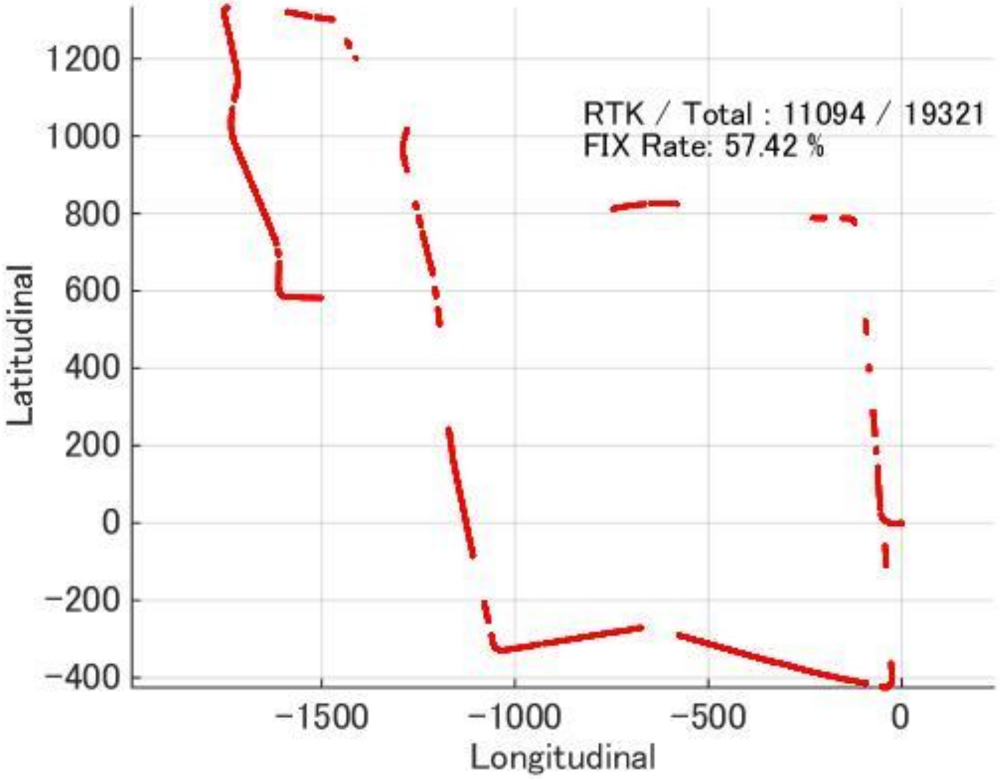
●Trajectory ●Under pass

RTK-GNSS Performance



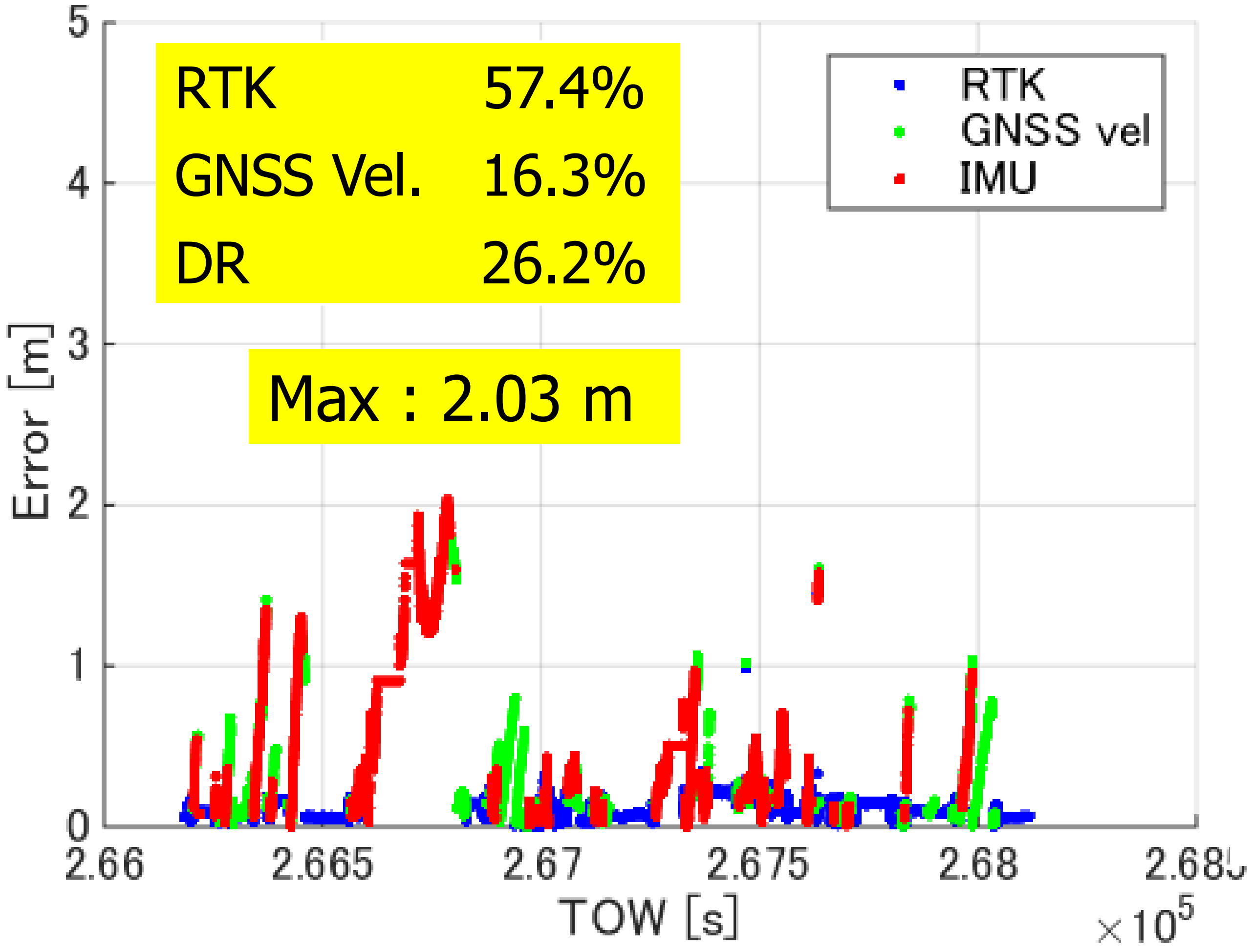


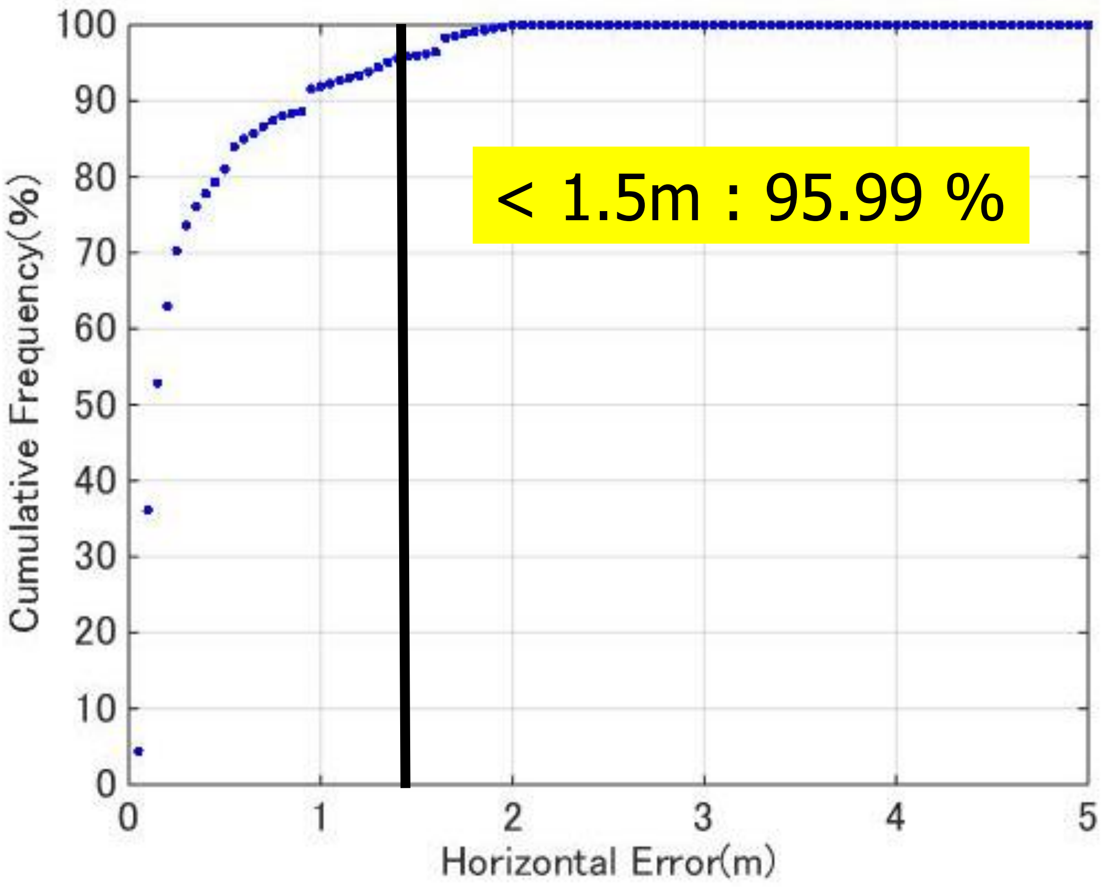
Sys.	Availability
GPS	25.8 %
GPS/QZS	37.3 % (**+11.5 %**)
GPS/QZS/BDS	57.4 % (+20.1 %)



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

Overall Results





Protection Level Estimation

- 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.

- RTK is not difficult to estimate the accuracy except for the wrong fixes.

- GNSS based velocity, instantaneous accuracy of velocity is not difficult to estimate. but we need to consider the degradation if we use this velocity continuously because there is a bias term.

- In the same manner, it is possible to estimate the positioning accuracy according to the empirical performance of the sensors for Dead Reckoning solutions by using IMU and speed sensor.

Protection Level Estimation

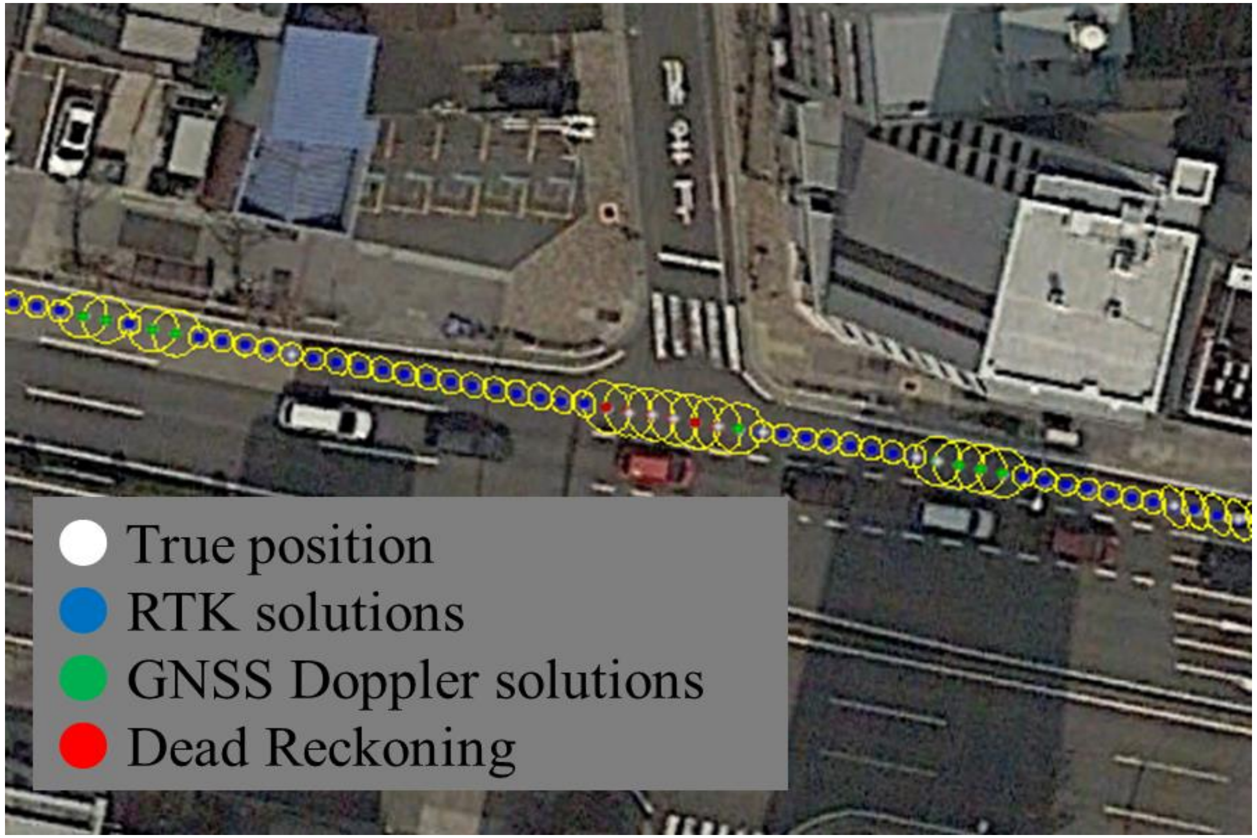
- The covariance ellipse by satellite constellation

$$\frac{x^2}{\sigma_x^2} - 2\rho_{xy}\frac{xy}{\sigma_x\sigma_y} - \frac{y^2}{\sigma_y^2} = (1-\rho_{xy}^2)C$$

$$P = 1 - \exp\left(-\frac{C}{2}\right)$$

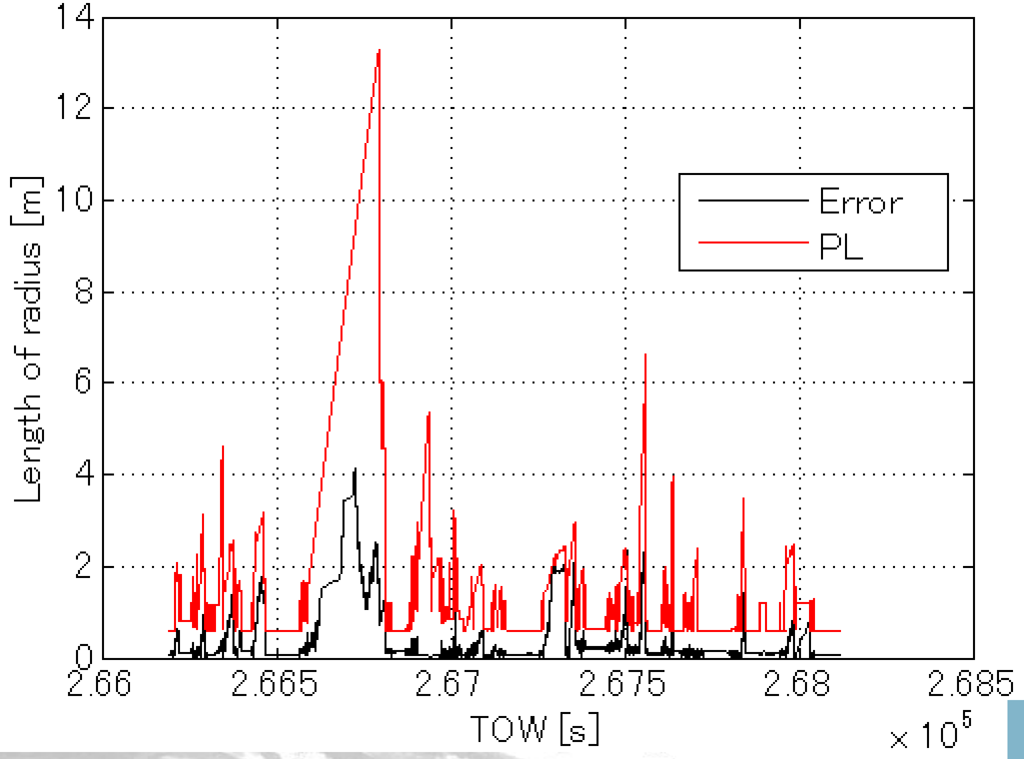
- Considered accumulating bias errors in GNSS-velocity and DR solutions.

Parameter	Value
RTK-GNSS error (m)	0.025
GNSS-velocity error (m/s)	0.02
IMU+Speed sensor error (m/s)	0.03

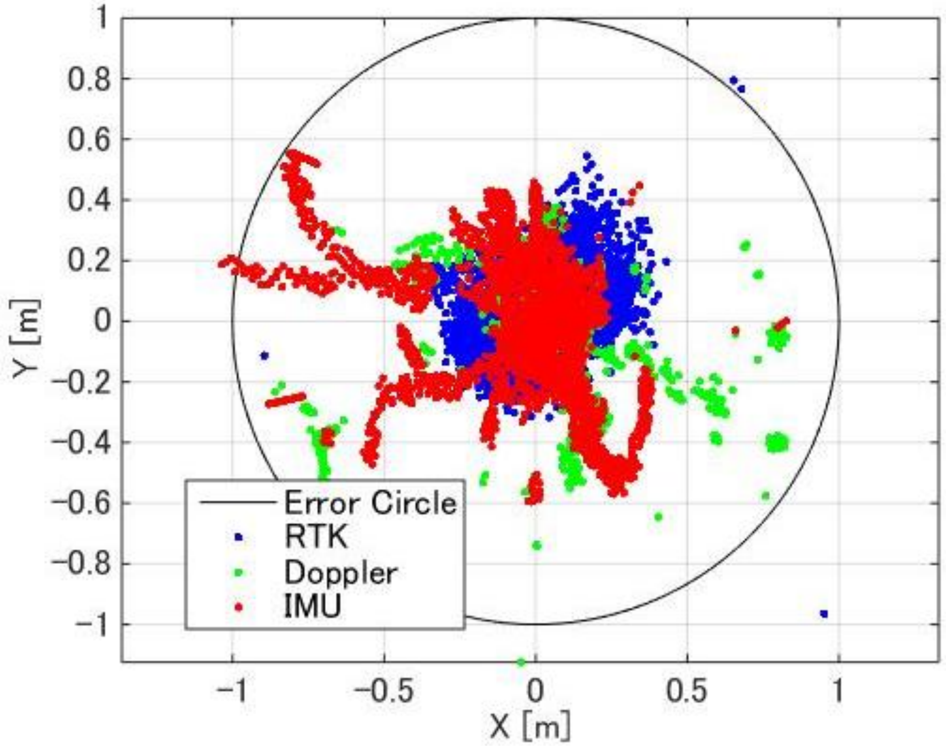


Protection Level Estimation

Coordinate transformation of the ellipse and true positions, plotting in time series stretched to fit the positioning error to the major axis of the ellipse figure.



Coordinate transformation of the ellipse and true positions, plotting the positioning distribution within 1m unit circle.



P value	Total	RTK	GNSS vel.	DR
0.99	99.3 %	99.9 %	99.6 %	98.1 %
0.999	99.9 %	99.9 %	99.9 %	99.9%

Summary

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

- 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.

- Protection level estimated by simple way.
  The resulted probability as it is set.

Future Work

- Integrity monitoring
  Apply Advanced RAIM methods in GNSS Real-Time Kinematic (RTK) positioning and when GNSS is integrated with other sensors for vehicle positioning.
  Mainly restrict our focus to horizontal positioning.

$y = Gx + \varepsilon$ $\quad S = (G^T W G)^{-1} G^T W \quad W = Q_y^{-1} \quad Q_{E,N} = S W^{-1} S^T$

$$G_{r,v}^{k,l} = \begin{bmatrix} \left(-cos\epsilon^k sin\theta^k + cos\epsilon^l sin\theta^l\right)_r - \left(-cos\epsilon^k sin\theta^k + cos\epsilon^l sin\theta^l\right)_v \\ \left(-cos\epsilon^k cos\theta^k + cos\epsilon^l cos\theta^l\right)_r - \left(-cos\epsilon^k cos\theta^k + cos\epsilon^l cos\theta^l\right)_v \\ \left(-sin\epsilon^k + sin\epsilon^l\right)_r - \left(-sin\epsilon^k + sin\epsilon^l\right)_v \end{bmatrix}^T$$

$$HPL_{RTK} = K_{fa(H),i} \times \sigma_{dH,i} + K_{md,i} \times \sigma_{H,i}$$

$$HPL_{DR} = K_{fa(H)} \times \sigma_{dH} + H(|S|) bias_{\theta IMU}$$

$$HPL_{vel} = K_{fa(H)} \times \sigma_{dH}$$

$$G_{DR} = \begin{bmatrix} \dfrac{\Delta N csc^2\left(\frac{\Delta N}{\Delta E}\right)}{\Delta E^2} & -\dfrac{csc^2\left(\frac{\Delta N}{\Delta E}\right)}{\Delta E} \\ \dfrac{\Delta E}{\Delta t\sqrt{\Delta E^2 + \Delta N^2}} & \dfrac{\Delta N}{\Delta t\sqrt{\Delta E^2 + \Delta N^2}} \end{bmatrix} \quad G_{vel} = \begin{bmatrix} \frac{1}{\Delta t} & 0 \\ 0 & \frac{1}{\Delta t} \end{bmatrix}$$

$Q: covariance\ matrix \quad K_{md,i} = 1.2816 \quad K_{fa(H)} = 2.44775$

Thank you for your attention !