Performance Evaluation of GNSS Based Railway Applications

IAIN World Congress 2015, Prague, Czech Republic

Nobuaki Kubo, Motoki Higuchi and Tomoji Takasu

(Tokyo University of Marine Science and Technology)

Haruo Yamamoto

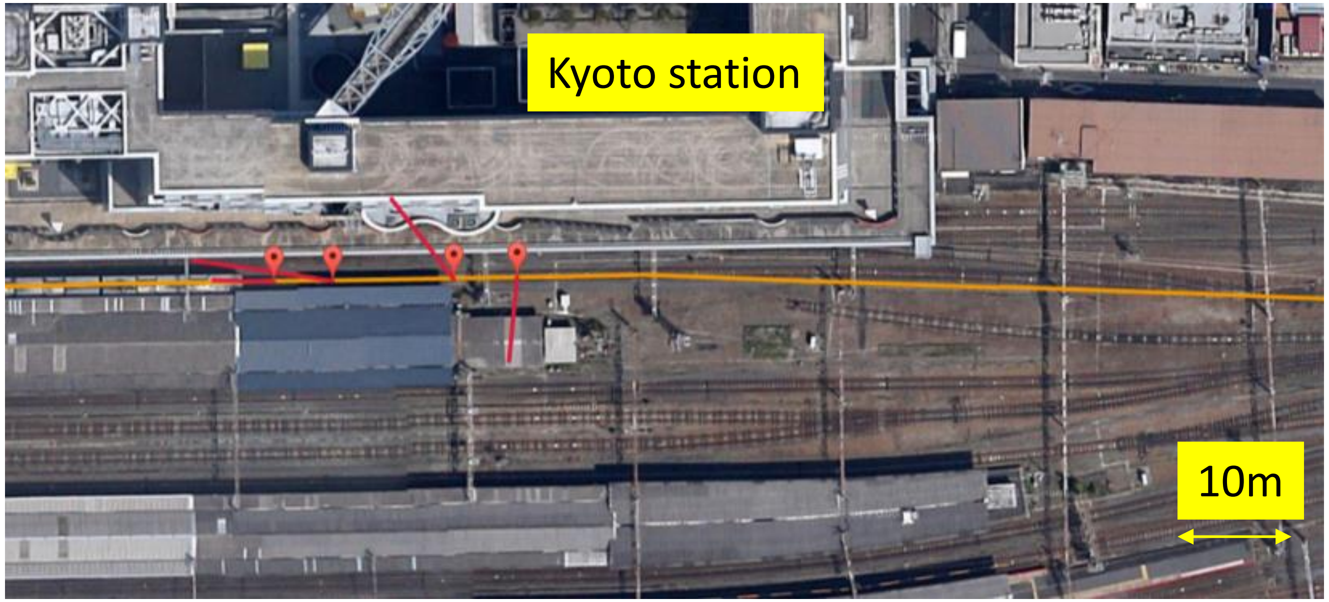
(Railway Technical Research Institute)

Outline

- Motivation
- Data Acquisition
- Multipath Error Analysis
- Multipath Error Mitigation and Results
- Conclusion

ここに最近のトピックを入れる

Motivation 1

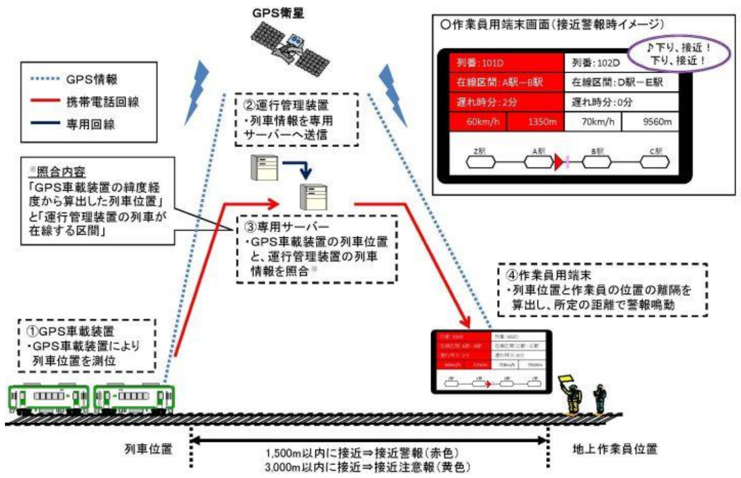


Google map

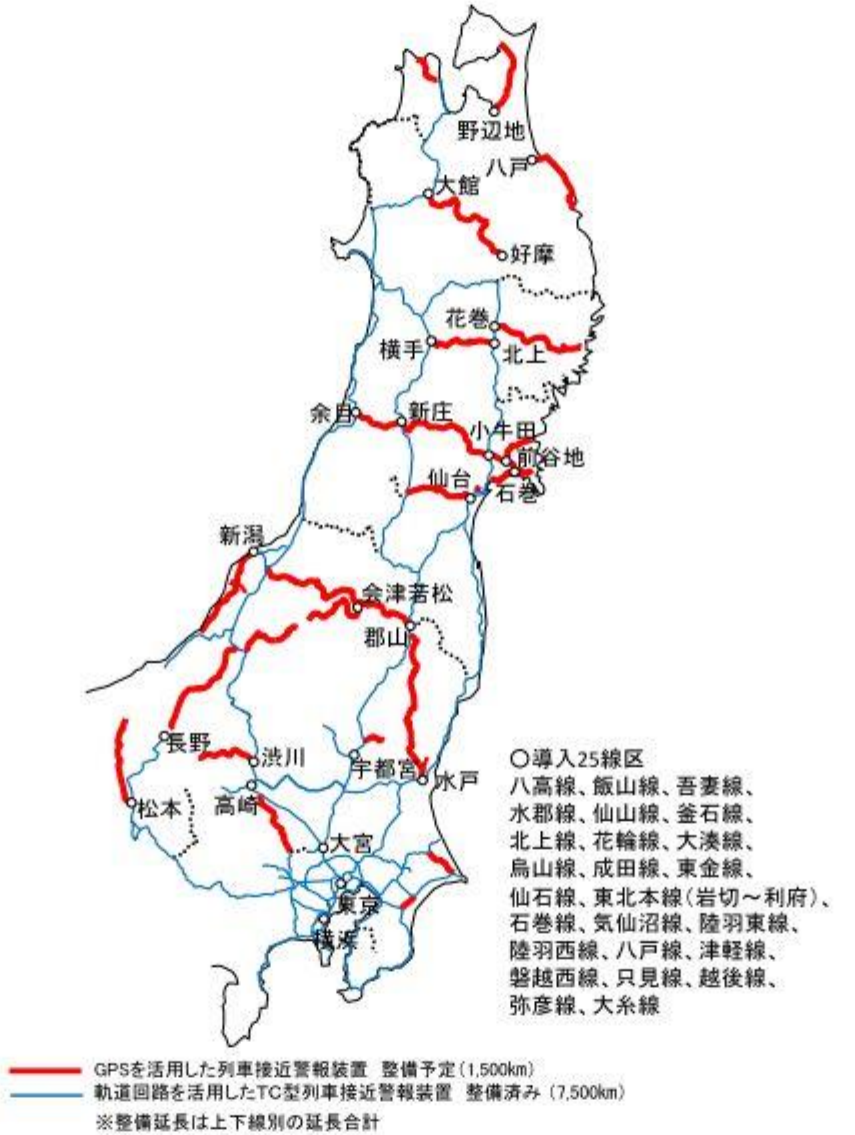
- What are the reasons of these errors ? (Multipath ?)
- How big of these errors ?
- The large errors usually occurs at same places like shown in these pictures.
- We need to know the actual performance using GNSS.
- If possible, we want to reduce these errors.

Motivation 2

- East Japan Railway Company plans to install the GNSS based warning device (routes in red) for train approach to protect the worker in the field.
- Red(warning) : 1500m   Yellow(caution) : 3000m
- Safety related applications requires **integrity and reliability**.
- For this purpose, **performance analysis in the real railway environment** is quite important.

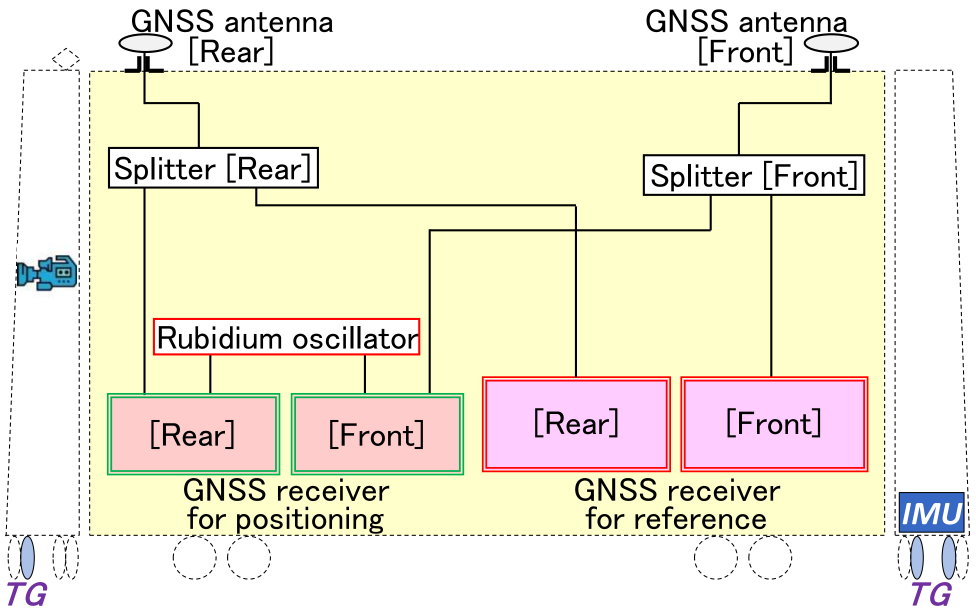


GPSを活用した列車接近警報装置を導入する線区



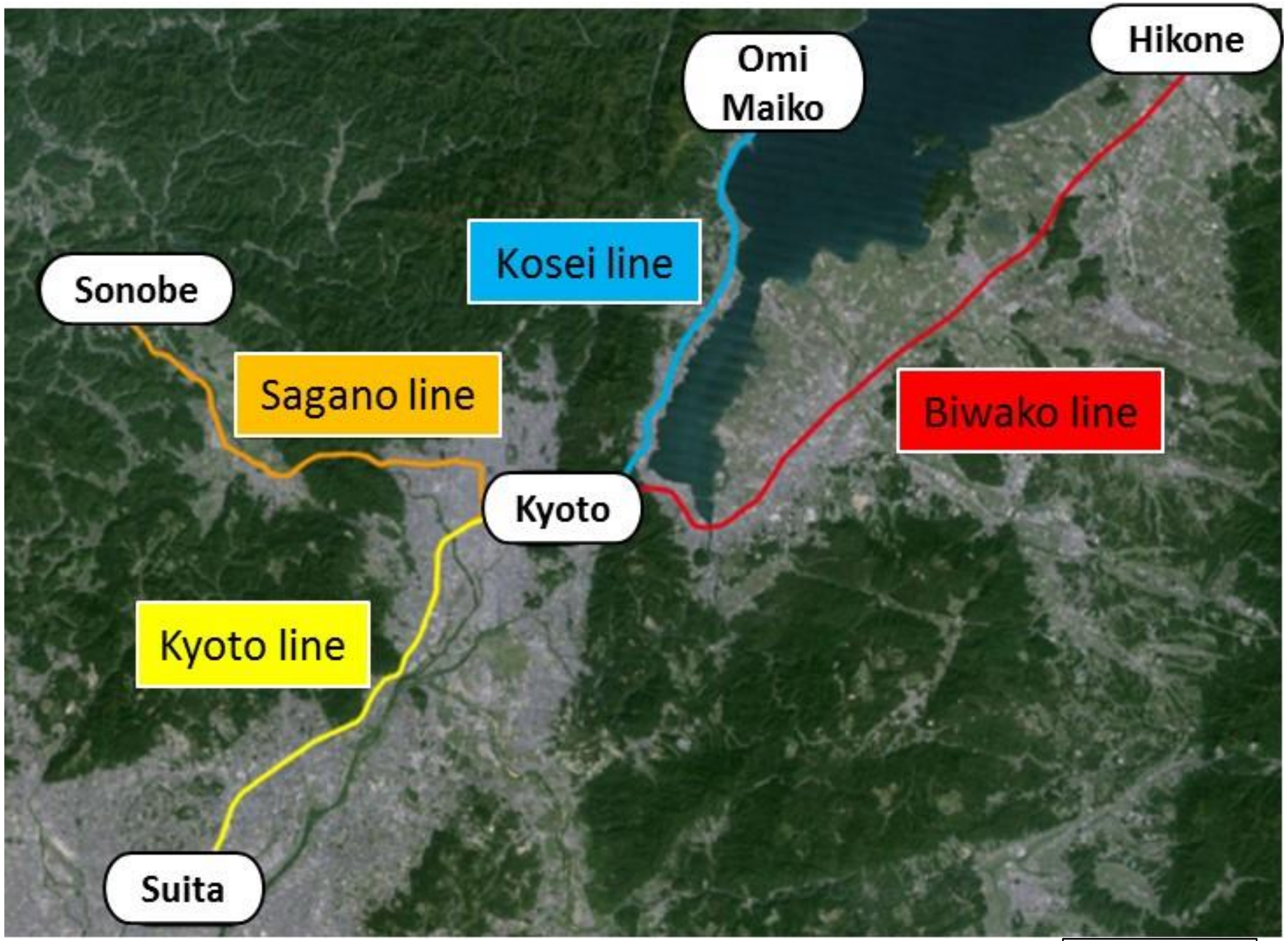
Data Acquisition 1

Test Train for Conventional Line (U@tech)



Interval	0.1 s
Receiver 1	JAVAD Delta-G3T
Receiver 2	NovAtel OEM628
Antenna	NovAtel GPS-703-GGG
Antenna interval	18.21 m
Rubidium oscillator	Stanford Research Systems FS725
Reference station	Receiver : JAVAD Delta-G3T Antenna : JAVAD GrANT-G3

Data Acquisition 2



Railway lines for test (West Japan Railway Area)

Google map

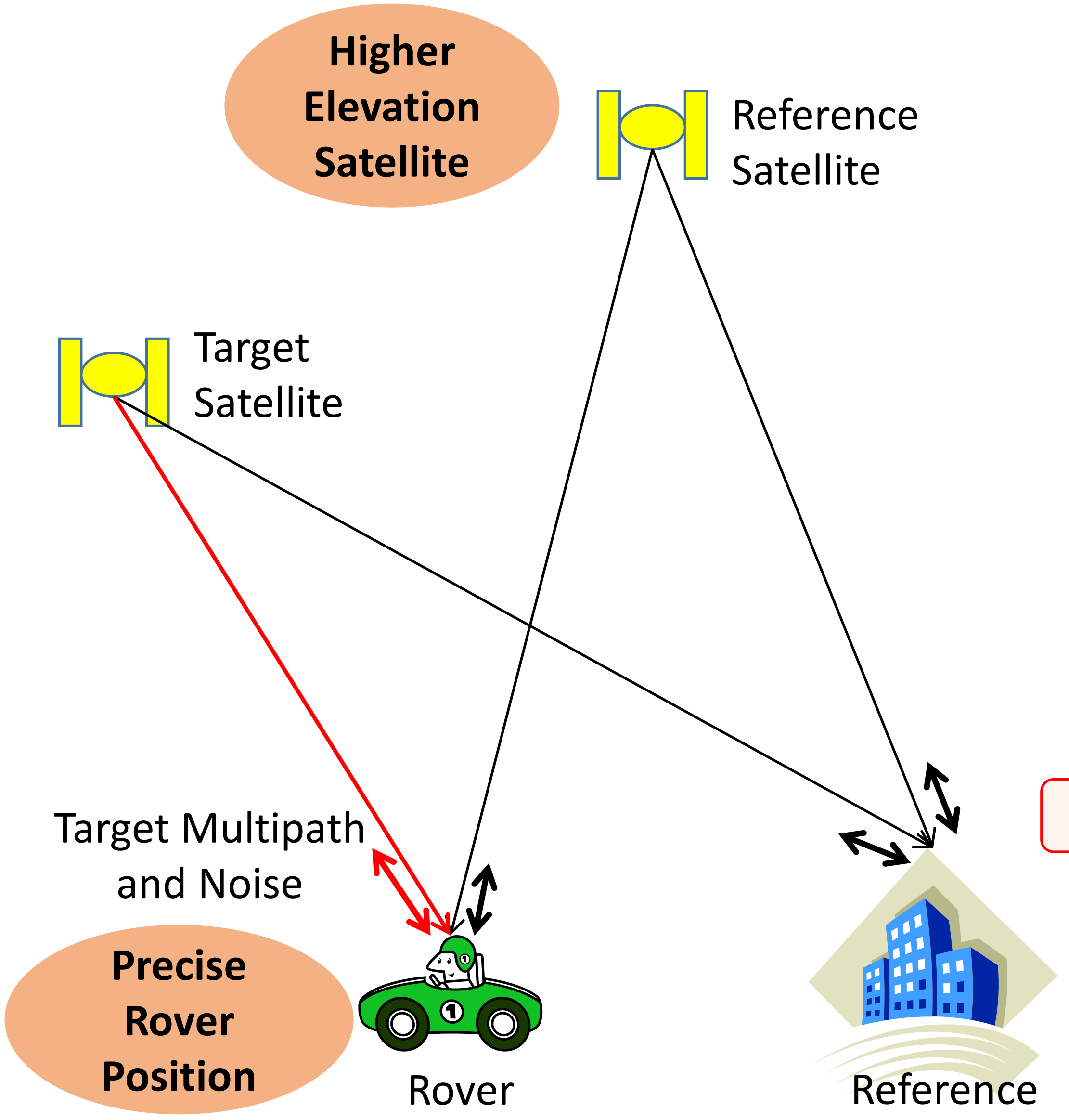
The observational data was collected in sections totaling 171 km on four operating lines extended in four directions from JR Kyoto Station.

Urban areas including spots like the valley of the buildings, plain areas of the suburbs where the sky is open and mountainous areas, etc. are given as the positioning environment. The tunnel also exists in part.

The observation was carried out from December, 2012 to February, 2013, and the mileage amounted to a total of 2,000 km.

The kinematic reference positions used in this test were produced using both the antenna trajectory (GIS) and post-processed RTK positioning, and they were used to evaluate positioning performance in this paper.

Multipath Error and Noise Analysis



$$P_{rov\_ref}^{sv1\_sv2} = (P_{rov}^{sv1} - P_{ref}^{sv1}) - (P_{rov}^{sv2} - P_{ref}^{sv2})$$

$$= \rho_{rov}^{sv1} + c(dt_{sv1} - dT_{rov}) + ion_{rov}^{sv1} + tropo_{rov}^{sv1} + mp_{rov}^{sv1} + noise_{rov}^{sv1}$$

$$- \left[\rho_{ref}^{sv1} + c(dt_{sv1} - dT_{ref}) + ion_{ref}^{sv1} + tropo_{ref}^{sv1} + mp_{ref}^{sv1} + noise_{ref}^{sv1}\right]$$

$$- \left[\rho_{rov}^{sv2} + c(dt_{sv2} - dT_{rov}) + ion_{rov}^{sv2} + tropo_{rov}^{sv2} + mp_{rov}^{sv2} + noise_{rov}^{sv2}\right]$$

$$+ \left[\rho_{ref}^{sv2} + c(dt_{sv2} - dT_{ref}) + ion_{ref}^{sv2} + tropo_{ref}^{sv2} + mp_{ref}^{sv2} + noise_{ref}^{sv2}\right]$$

$$= \rho_{rov}^{sv1} - \rho_{ref}^{sv1} + \rho_{rov}^{sv2} - \rho_{ref}^{sv2}$$

$$+ (mp_{rov}^{sv1} + noise_{rov}^{sv1}) - (mp_{ref}^{sv1} + noise_{ref}^{sv1})\ ①$$

$$- (mp_{rov}^{sv2} + noise_{rov}^{sv2})\ ② + (mp_{ref}^{sv2} + noise_{ref}^{sv2})\ ③$$

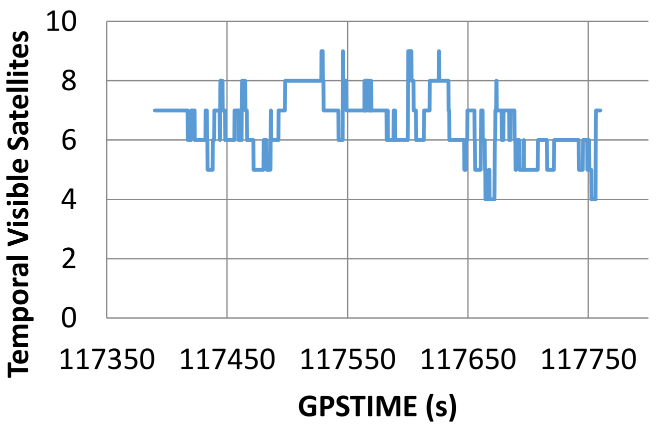
Target = Raw Data − Measurements + ① + ② − ③

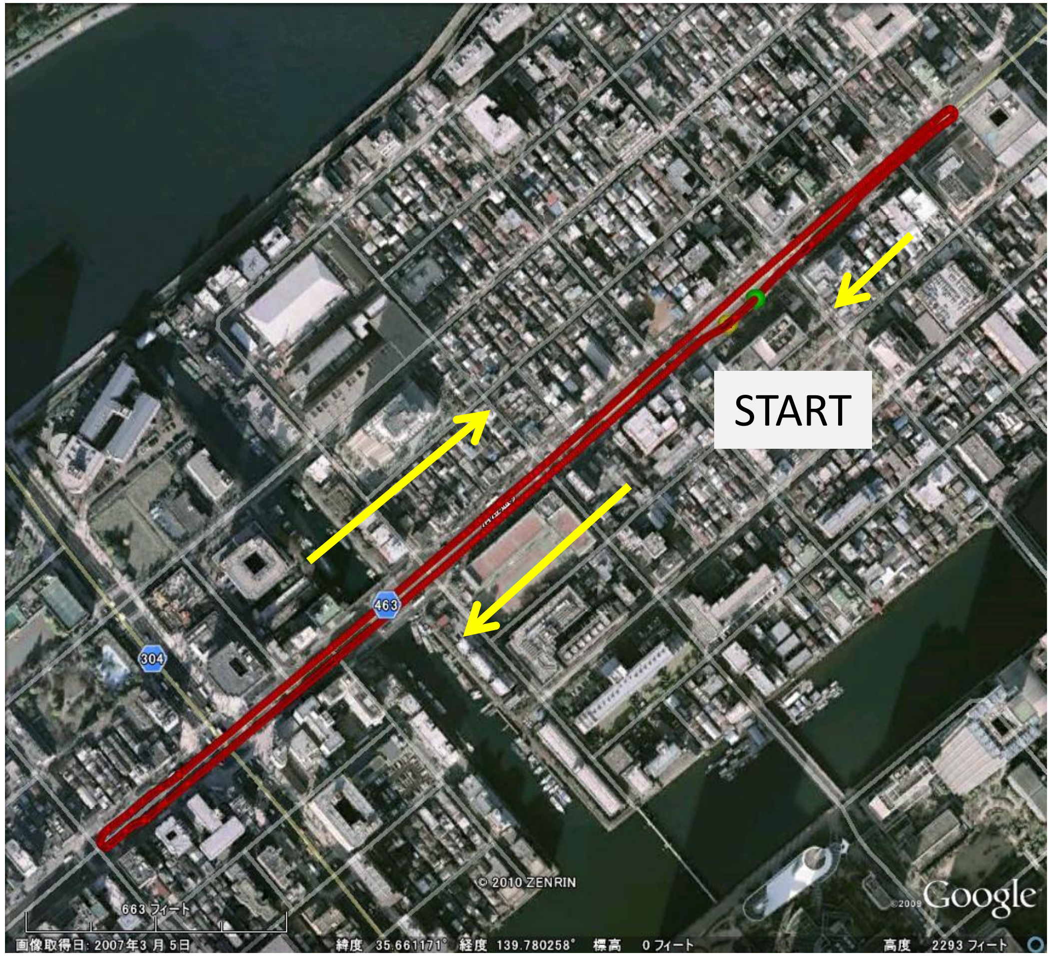
(① + ② − ③: CC-Difference)

sv1 : Target SV sv2 : Reference SV (Max Elevation)

Validation of the Proposed Method

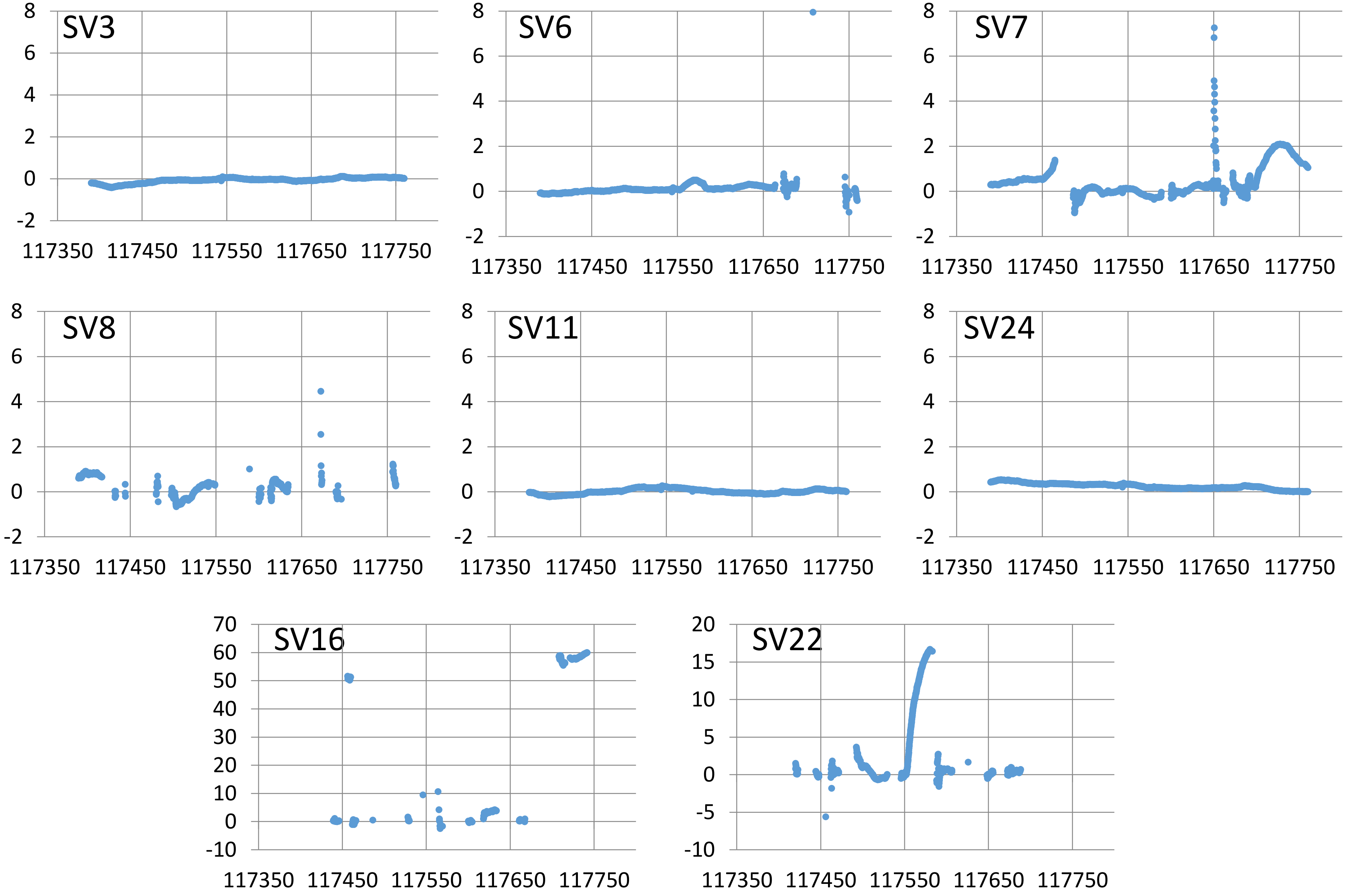
- Test using car in the medium urban areas (Tokyo)
- 6 min 30 sec (5 Hz)
- Geodetic dual frequency receiver and antenna
- Reference station was our building
- Reference SV: PRN-19 (66 degree)
- 9 satellites in view over 10 degree elevation
- Precise car positions were computed by post-processing RTK.



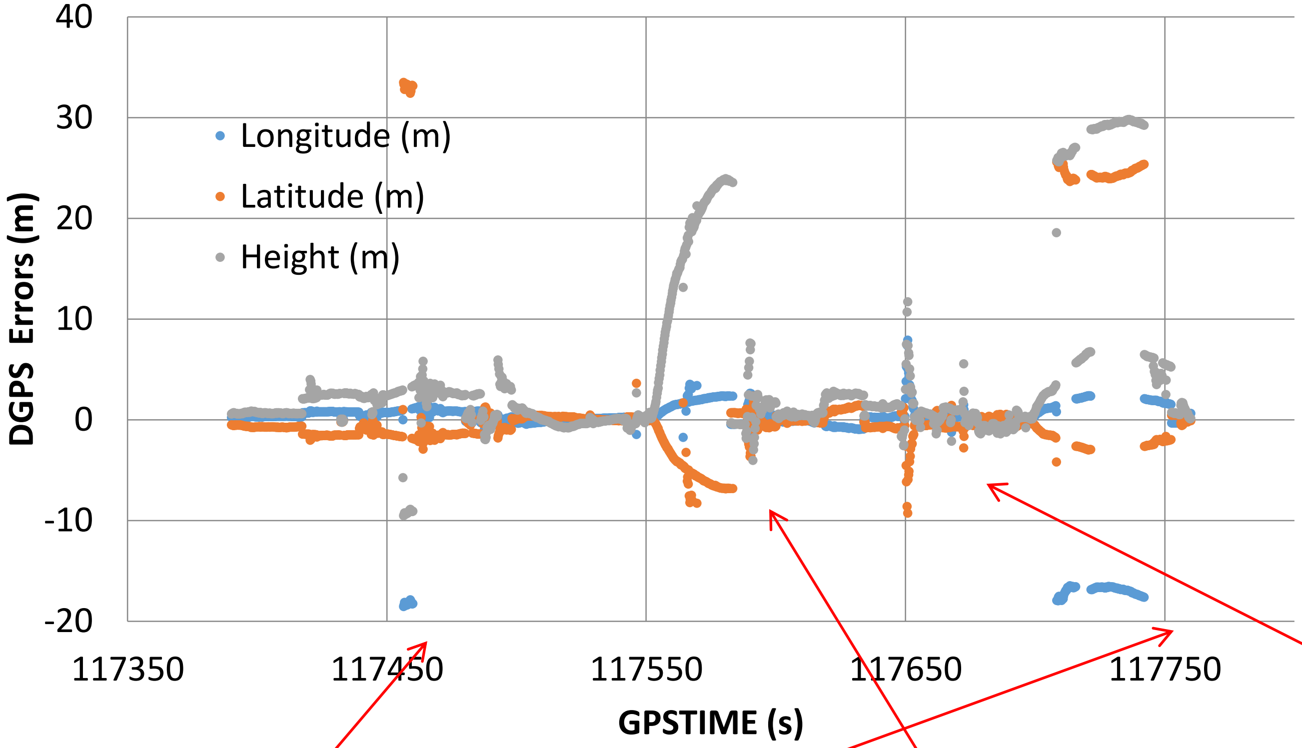


Test route

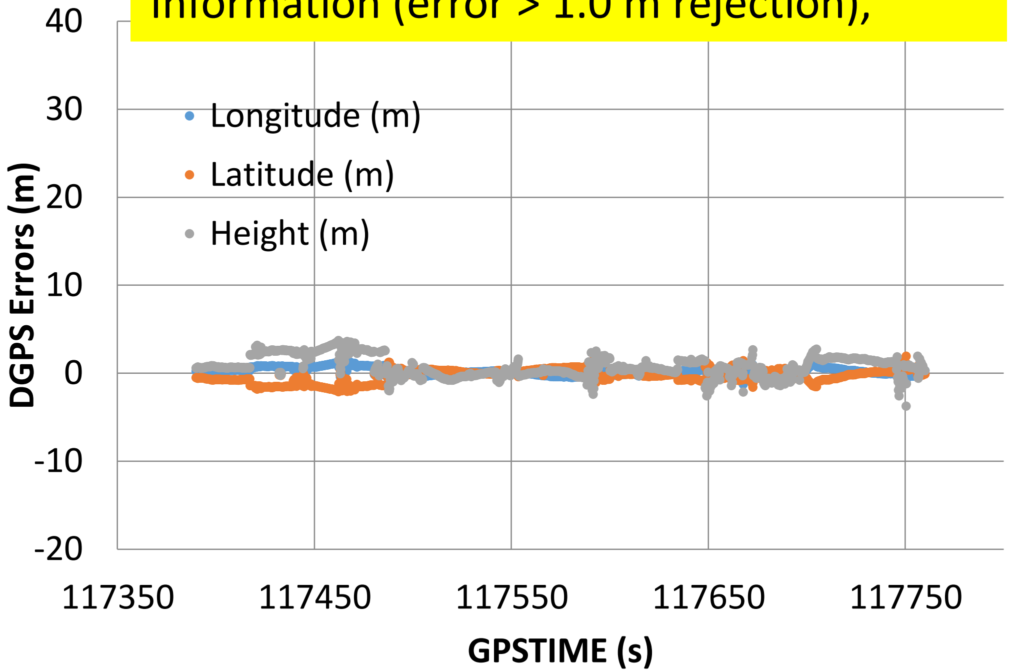
Temporal Multipath Errors and Noise of Each Satellite using the Proposed Method



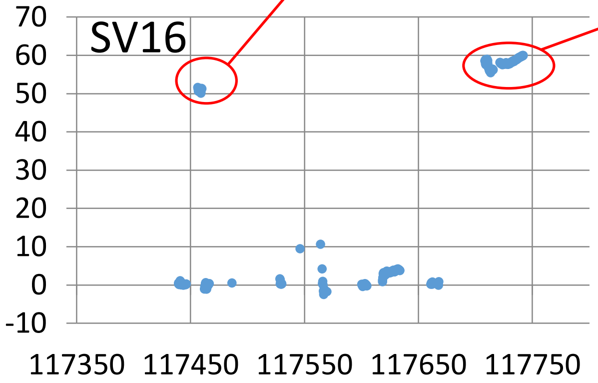
Pseudo-range DGPS Error Analysis

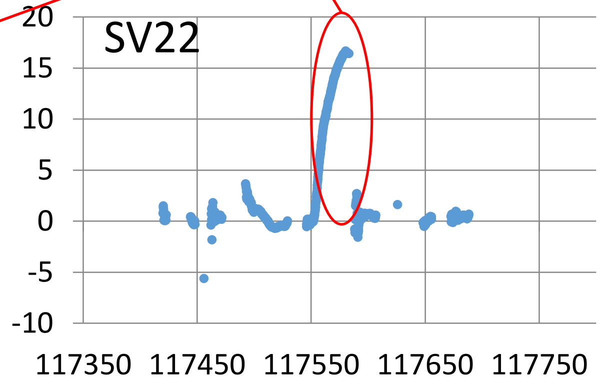


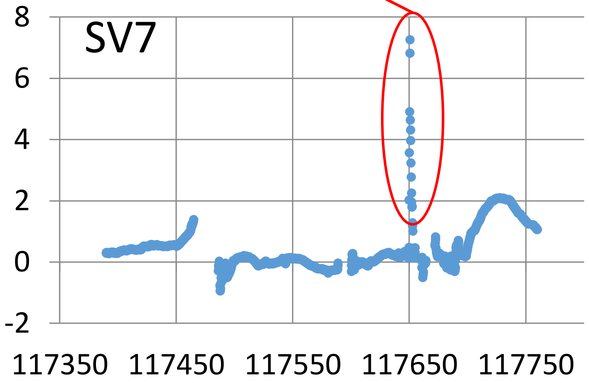
If we select the satellite using the previous Information (error > 1.0 m rejection),



	Average NVS	Horizontal (1σ)	Vertical (1σ)
Normal	**6.49**	**9.07 m**	**8.54 m**
+MP rejection	**6.08**	**0.81 m**	**1.13 m**







Error Analysis under Real Railroad Environment

Analysis condition

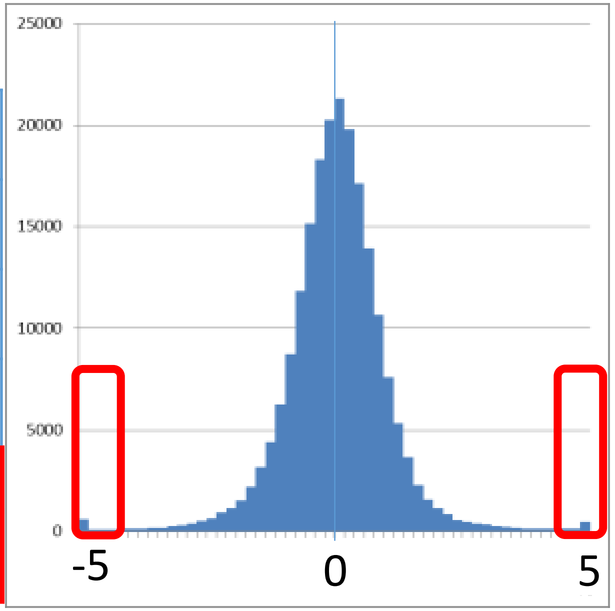
Satellite	GPS and QZSS
Minimum C/N0	25 dB-Hz
Mask angle	10 degree
Reference satellite	Maximum elevation and C/N_0 > 43.0 dB-Hz
GDOP	< 30
Interval	1.0 sec
Smoothing	Not applied (default 2 sec in JAVAD receiver)

Pseudo-range errors were analyzed using the previous method.
The data while the train stopped at the station was not included.
DGNSS (GPS/QZS) was also evaluated.

Test Results of Each Line

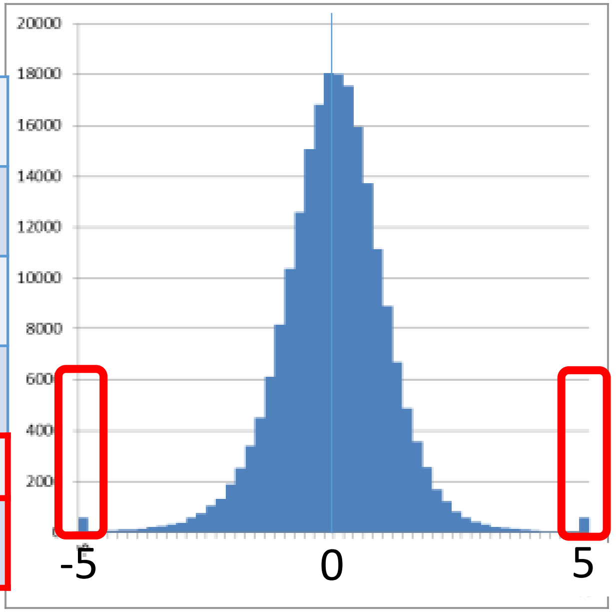
Sagano

Total	34138 s
1σ	1.17 m
Average	0.04 m
Maximum	40.1 m
99.9 %	8.8 m
99.99 %	19.4 m



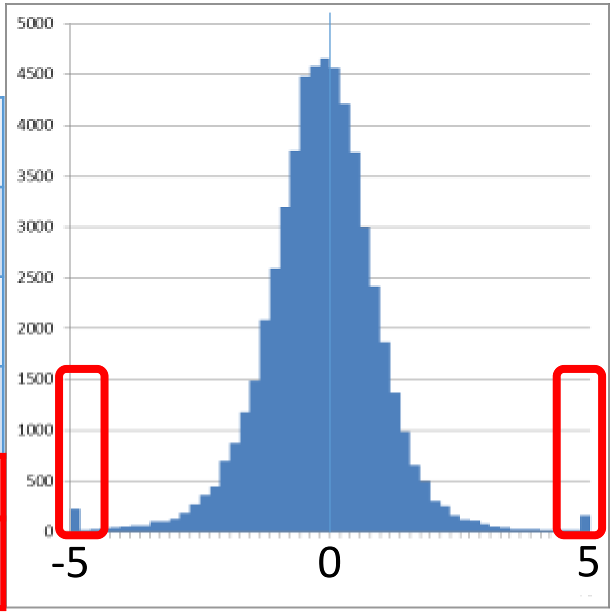
Kosei

Total	43064 s
1σ	1.43 m
Average	0.01 m
Maximum	53.3 m
99.9 %	15.4 m
99.99 %	32.3 m



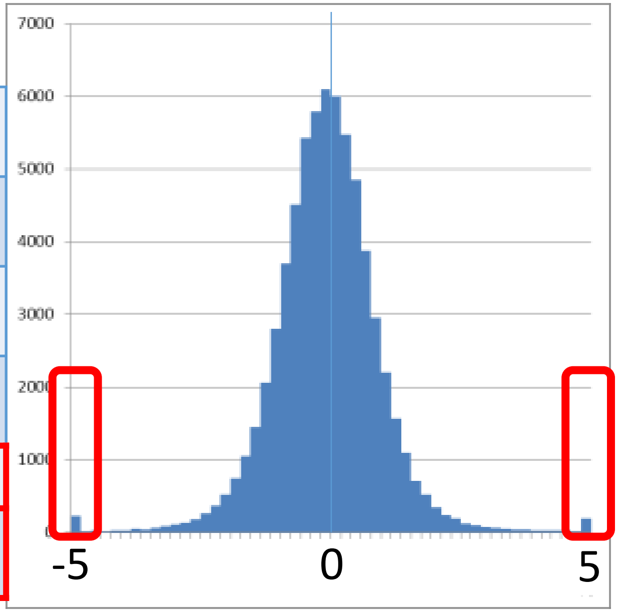
Kyoto

Total	9318 s
1σ	1.32 m
Average	-0.17 m
Maximum	49.9 m
99.9 %	10.3 m
99.99 %	19.8 m



Biwako

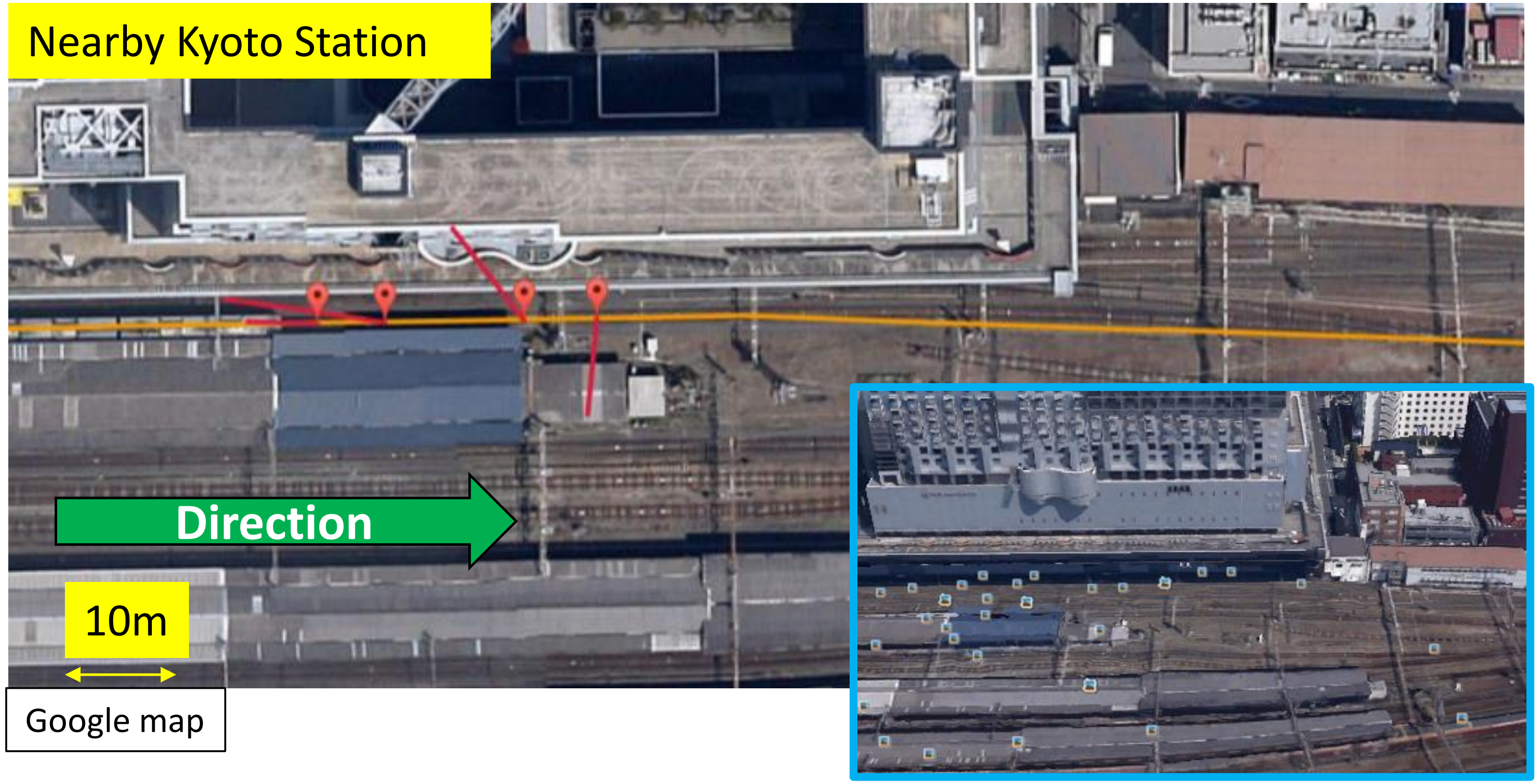
Total	10735 s
1σ	1.317 m
Average	-0.08 m
Maximum	43.3 m
99.9 %	9.3 m
99.99 %	16.1 m



マルチパス誤差とDGPSの誤差の関係

One Shot of Large Errors nearby Kyoto Station

Heavily deteriorated satellite（Ele=41, Azi=162）				
Places (from left)	①	②	③	④
Pseudo-range Error[m]	7.6	18.9	15.3	-7.9
Actual Error [m]	8.3	19.4	14.0	11.5



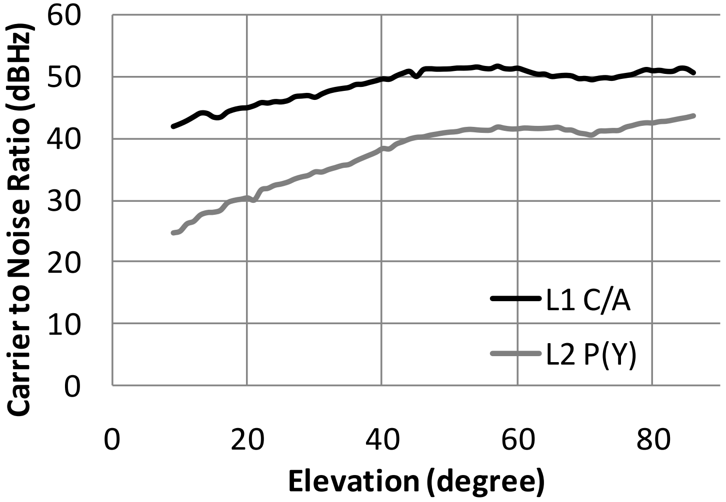
DGNSS errors strongly depends on the pseudo-range errors.

The pseudo-range errors over 10 m occurred at the following places.

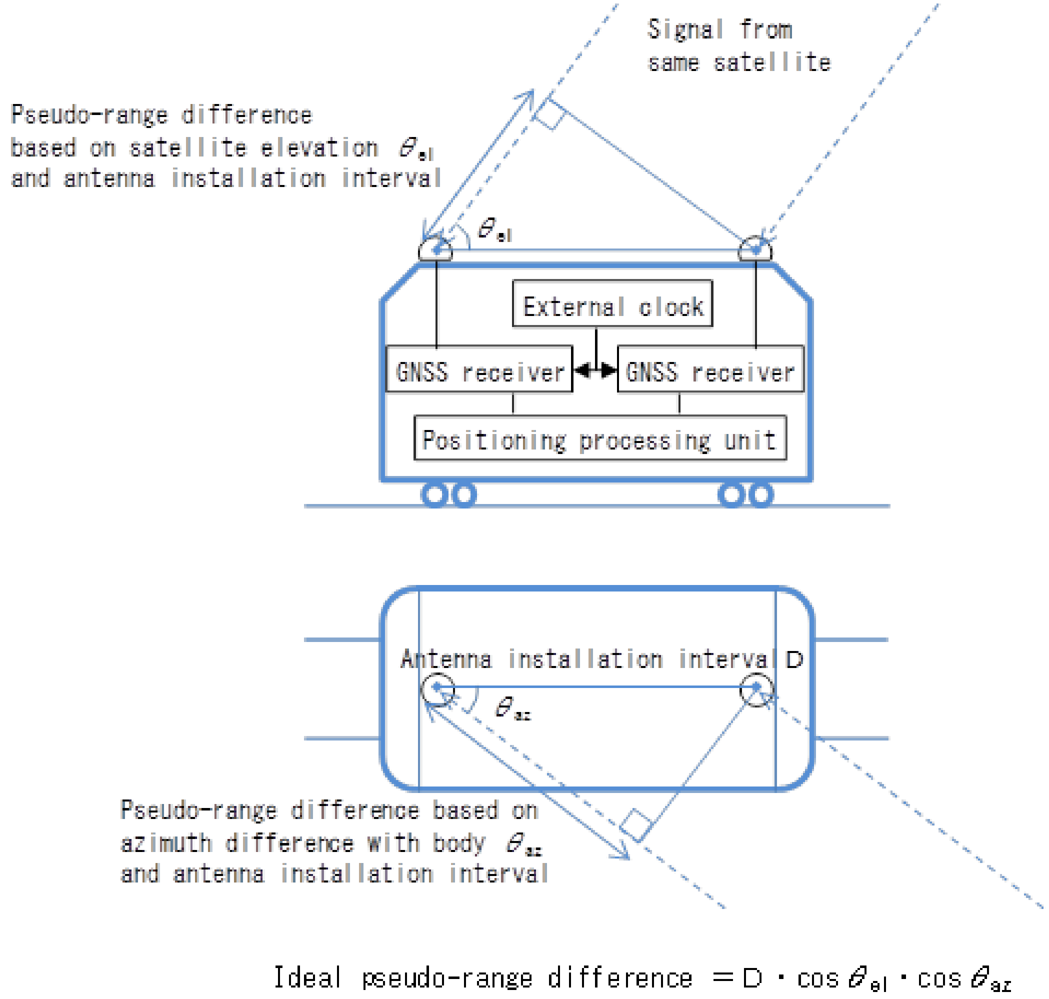
1) Nearby station
2) Under or nearby overpass
3) Close to hill or mountain
4) Both ends at tunnel

Proposed Pseudo-range Error Mitigation

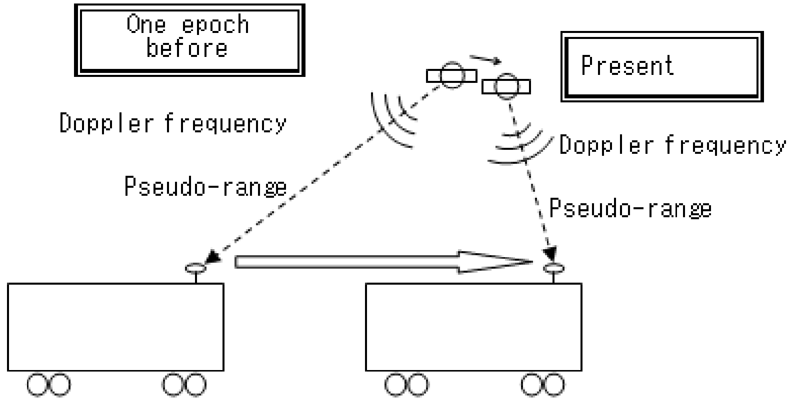
1. Elevation dependent C/N_0 threshold



3. Use of the antenna installation intervals



2. Doppler frequency based satellite selection

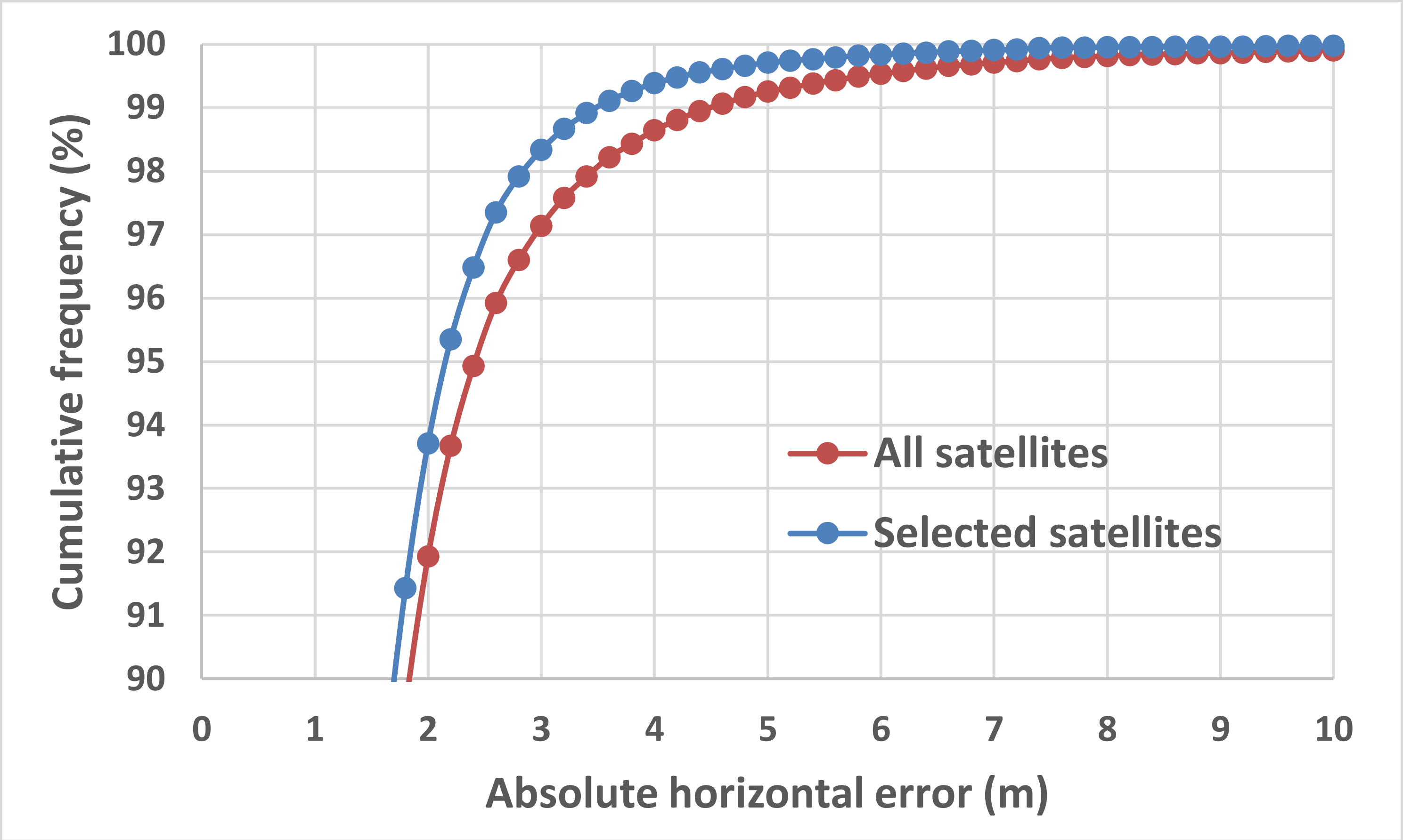


Evaluation of the Multipath Mitigation Technique

- We compared the **pseudo-range errors** between the use of **all available satellites** and the use of **selected satellites** using the proposed three techniques.
- Data : “Kyoto” and “Biwako” line (3.5 hours, 12/11/2012)
- Based on our many experimental data, the thresholds were set. The following table summarizes statistical results comparing the two cases.

	All satellites used	**Selected satellites used**
Number of samples	97407	85421
1σ	1.32 m	1.11 m
Average	–0.17 m	–0.15 m
Maximum	38.7 m	21.6 m
Number of samples with error over 5 m	730	250

Cumulative Frequency of Horizontal Errors



Percentage Point	All satellites used	Selected satellites used
99.00%	4.6 m	3.5 m
99.90%	10.0 m	6.9 m

Loosely Coupled KF using Velocity Information

- Doppler frequency derived **"velocity"** is quite tolerant to strong multipath condition.
- Pseudo-range based **"position"** is not tolerant to strong multipath condition.
- We need to put them together efficiently.
- Data : "Kyoto" and "Biwako" line (3.5 hours, ***10Hz***, 12/11/2012)

実際の擬似距離とドップラ速度積分の例を見せる

$$x_{k+1} = Fx_k + Gw_k$$
$$y_k = Hx_k + v_k$$

$$\boldsymbol{x_k} = [x(k), y(k), v_x(k), v_y(k), a_x(k), a_y(k)]^{\mathrm{T}}$$

$$x(k+1) = x(k) + v_x(k)\Delta T + a_x(k)\Delta T^2/2.0$$
$$y(k+1) = y(k) + v_y(k)\Delta T + a_y(k)\Delta T^2/2.0$$
$$v_x(k+1) = v_x(k) + a_x(k)\Delta T$$
$$v_y(k+1) = v_y(k) + a_y(k)\Delta T$$

$$\boldsymbol{F} = \begin{bmatrix} 1 & 0 & \Delta T & 0 & \Delta T^2/2 & 0 \\ 0 & 1 & 0 & \Delta T & 0 & \Delta T^2/2 \\ 0 & 0 & 1 & 0 & \Delta T & 0 \\ 0 & 0 & 0 & 1 & 0 & \Delta T \\ 0 & 0 & 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 \end{bmatrix}$$

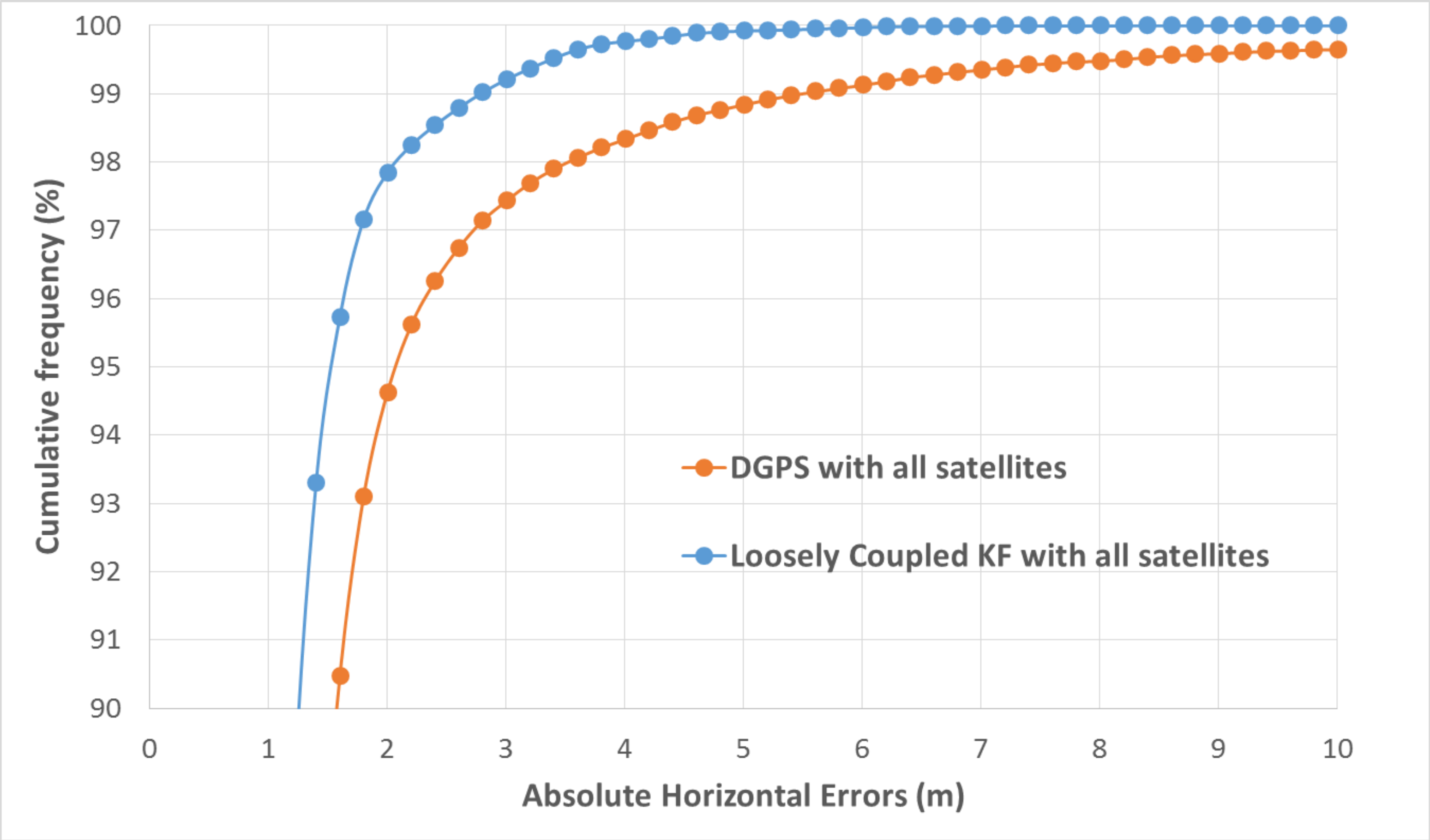
$$\boldsymbol{y_k} = [x(k), y(k), v_x(k), v_y(k)]^{\mathrm{T}}$$

$$\boldsymbol{H} = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix}$$

x_k : *state vector*
w_k : *system noise*
y_k : *measurement vector*
v_k : *measurement noise*

F : *state transition matrix*
G : *noise distribution matrix*
H : *observation matrix*

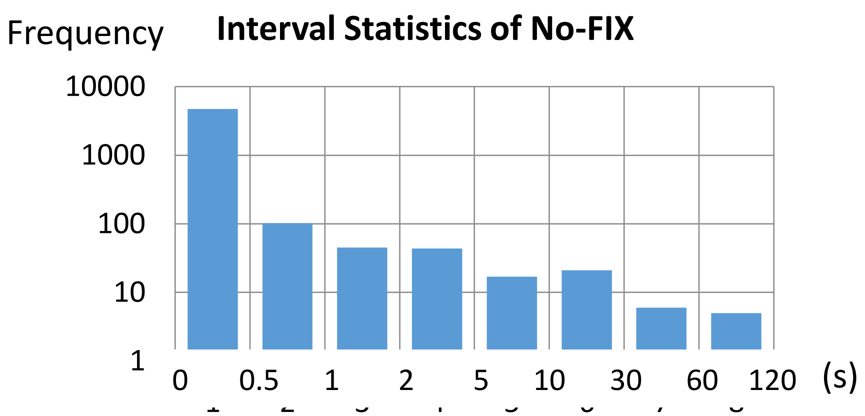
Cumulative Frequency of Horizontal Errors



Percentage Point	DGPS	Loosely Coupled KF
99.00%	5.4 m	2.8 m
99.90%	19.2 m	4.6 m
99.99 %	60.8 m	6.6 m

Conclusions

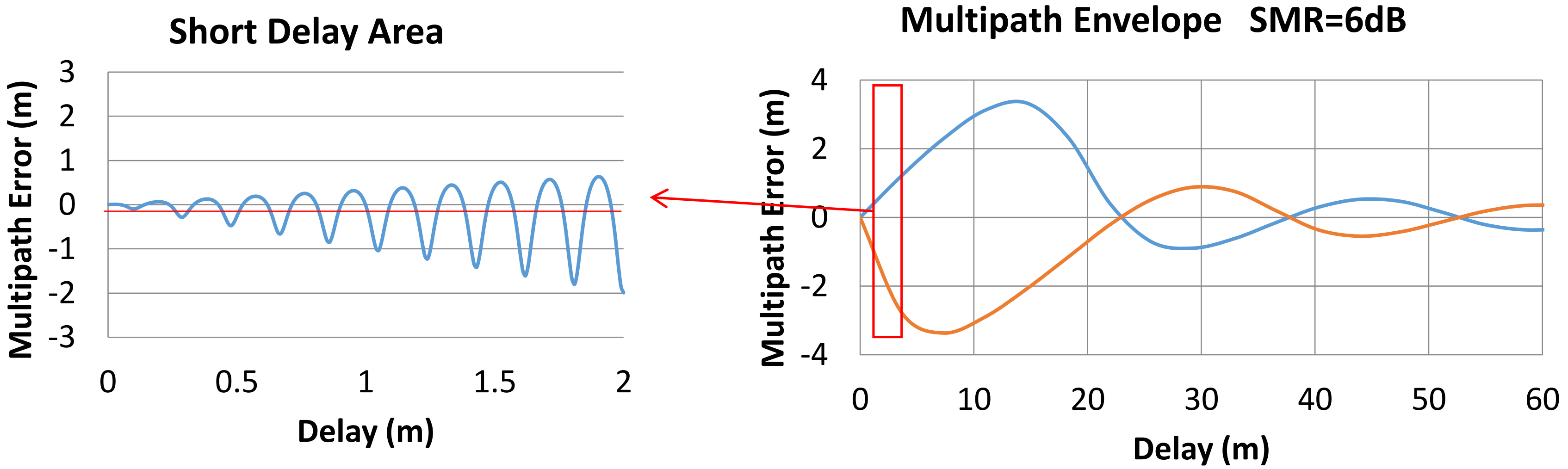
Appendix 1



Frequency
Interval Statistics of No-FIX
10000
1000
100
10
1
0
0.5
1
2
5
10
30
60
120
(s)

Appendix 2
(What if there is bias in “cc-difference”?)

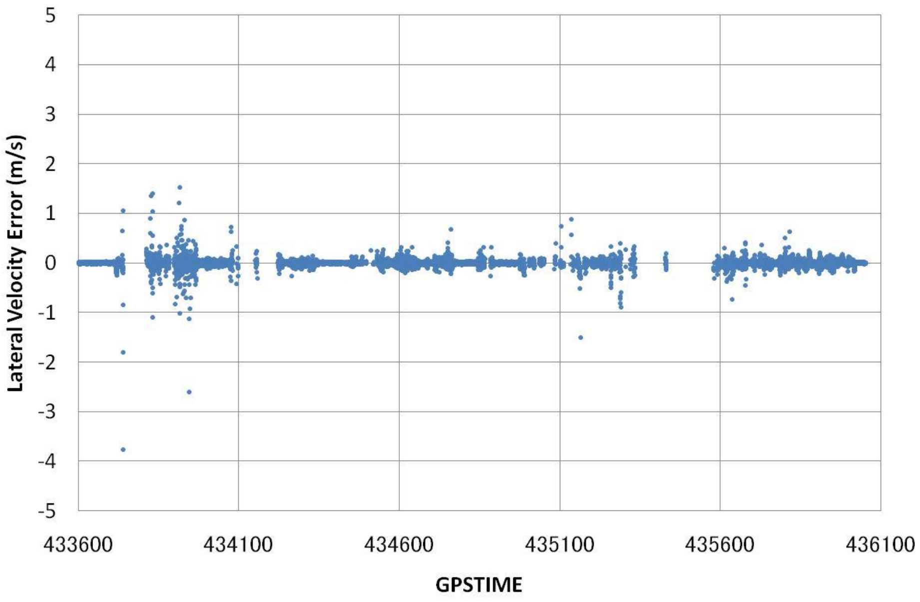
- In fact, there is a bias in multipath error derived from “cc-difference”.
- However, the long-term bias in the case of reference station (or high elevation satellite) is quite small like the following figure because of very short delay.

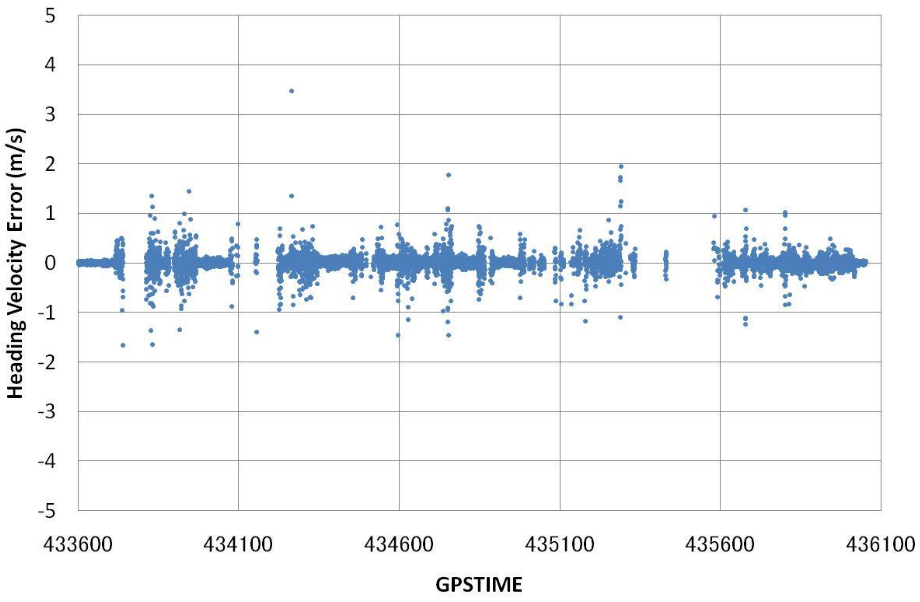


Bias is equal to <u>-0.16m</u>

Appendix 3

(velocity check in geodetic receiver)



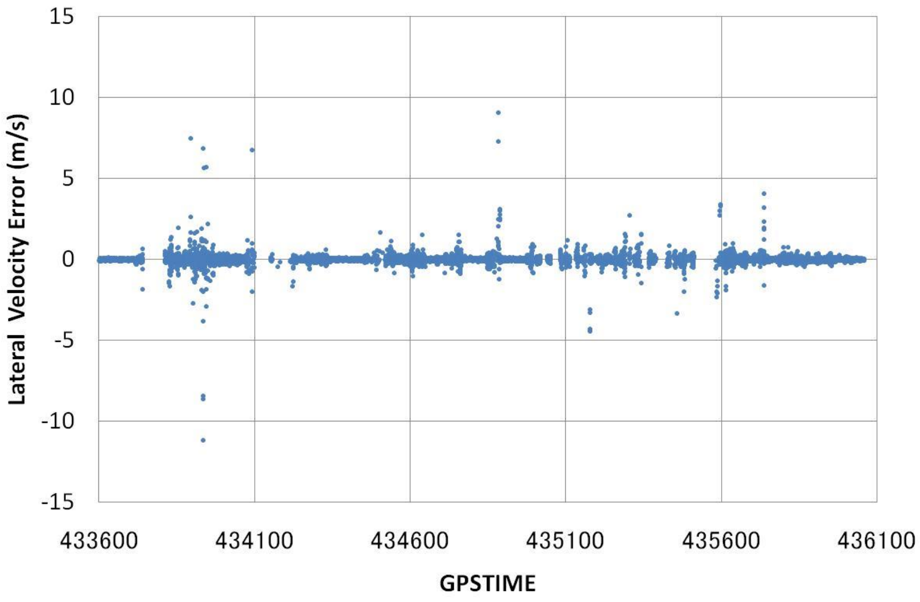


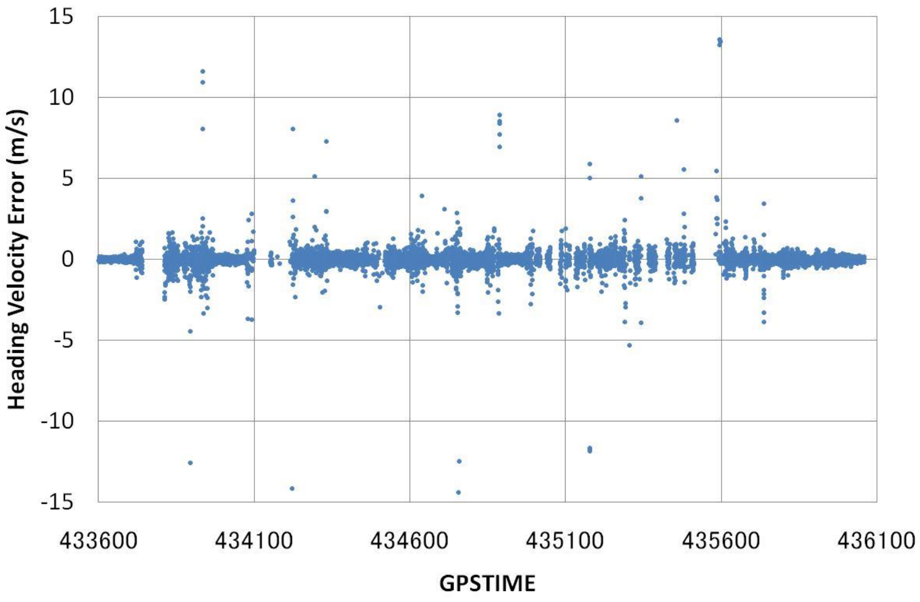
	Lateral	Heading	Availability
C/N_0 detection (7.0 dB)	10.8 cm	16.9 cm	67%
C/N_0 detection (10.0 dB)	13.9 cm	26.1 cm	74%

HDOP<10.0 Mask<15.0 C/N_0 >30.0

Appendix 4

(velocity check in high sensitivity receiver)

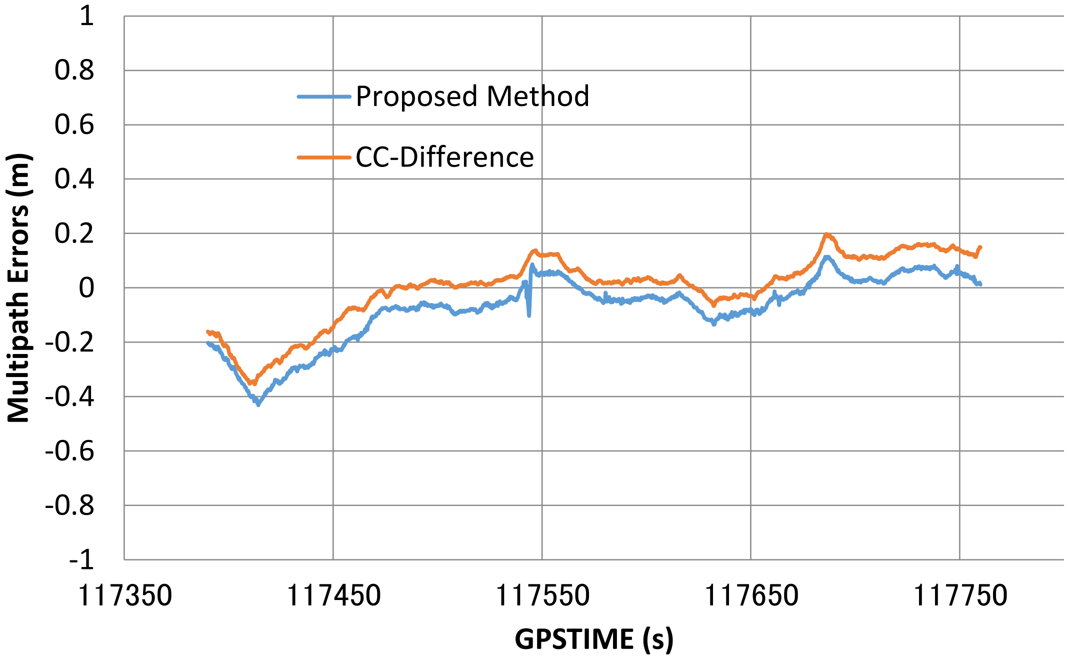




	Lateral	Heading	Availability
C/N_0 detection (7.0 dB)	38.4 cm	73.8 cm	72%
C/N_0 detection (10.0 dB)	47.1 cm	96.3 cm	80%

HDOP<10.0 Mask<15.0 C/N_0 >25.0

Validation of Multipath (PRN-3)



Multipath for PRN-3 derived from (DF) Code-Carrier Difference

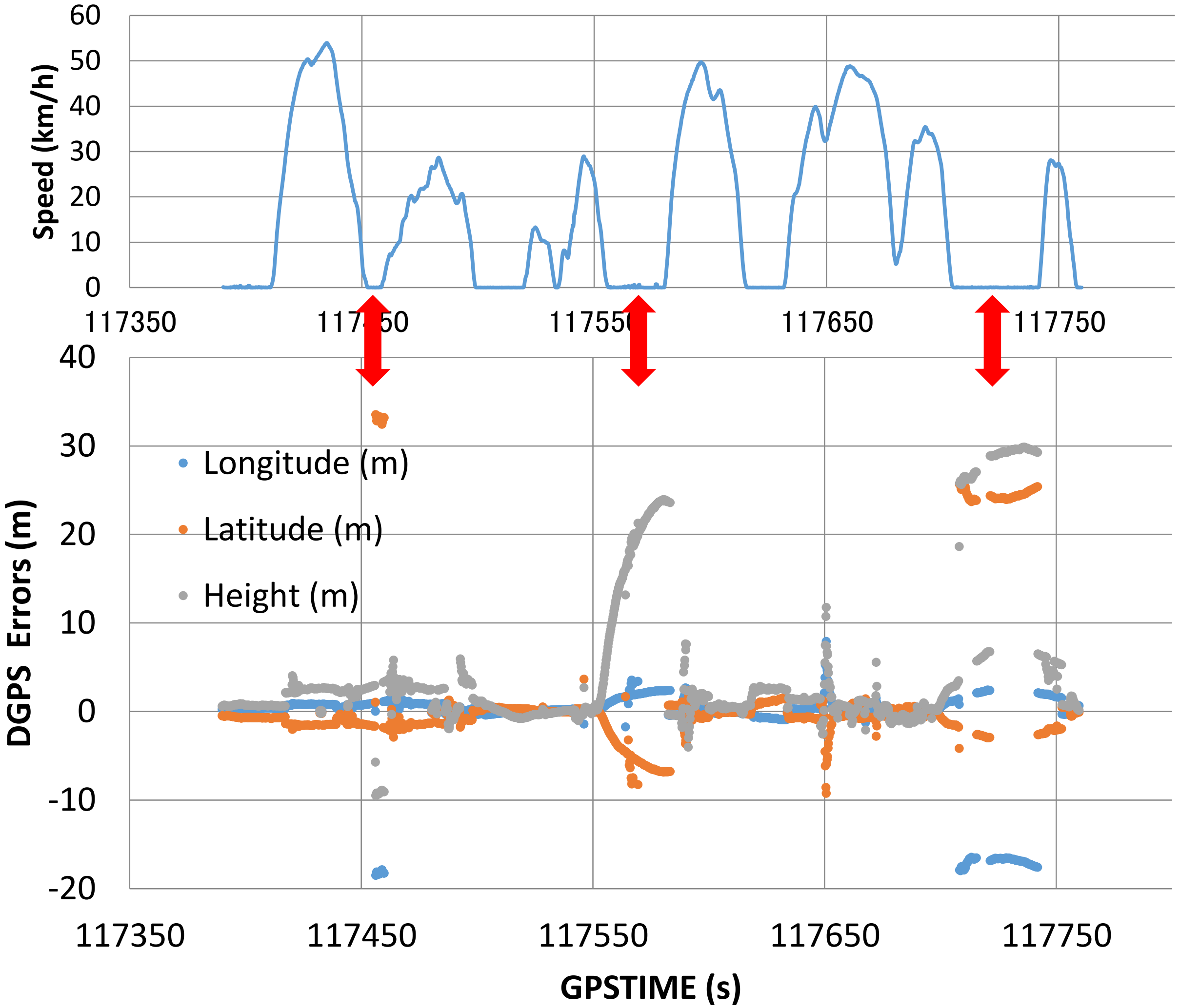
MATCH !

Multipath for PRN-3 derived from Proposed Method

Single Epoch RTK Processed in the Same Manner

	FIX Rate (Ratio >= 3.0)	Wrong FIX
Normal RTK	74.1%	0.0%
Normal RTK + MP rejection	92.0%	0.0%

Where or when is vulnerable to multipath?



When ?
Low Speed or Stop !

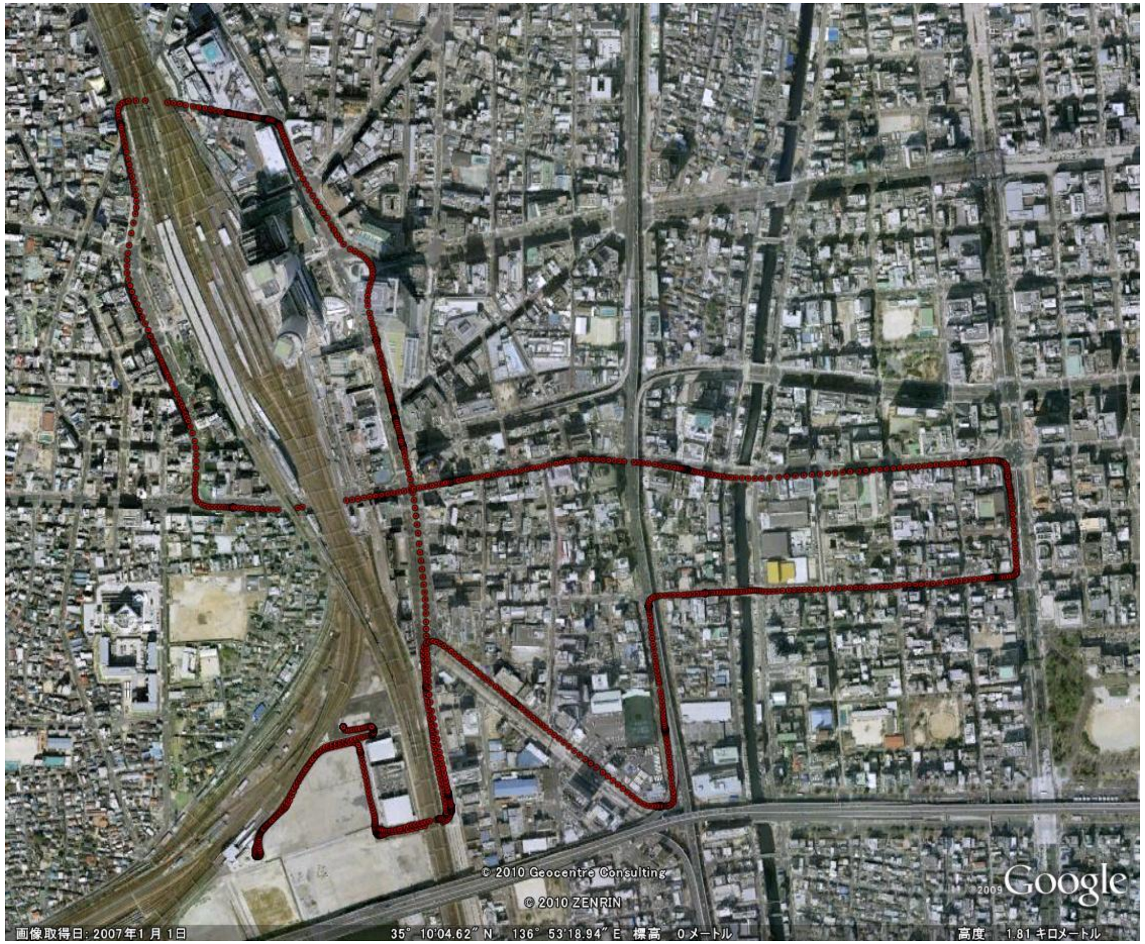
DGPS over 4 km/h

Horizontal (1σ)
9.07m → 1.32 m
Vertical (1σ)
8.54m → 2.60 m

Car Test 2

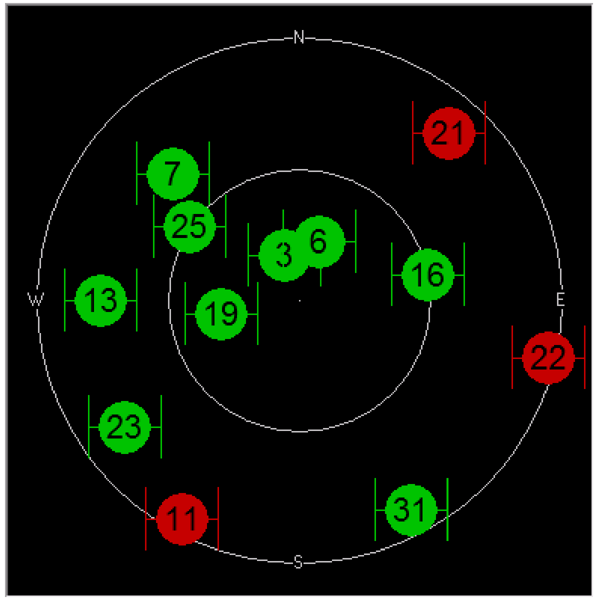
- 11/20/2009   40 min (5 Hz)
- Wide streets in dense-urban area (downtown Nagoya)
- Geodetic dual frequency receiver (same as before)
- Reference SV: PRN-19 (62 - 71 degrees elevation)
- 8-9 satellites in view over 10 degrees elevation
- Precise car position was post-processed by POSLV (provided by Toyota and Applanix).

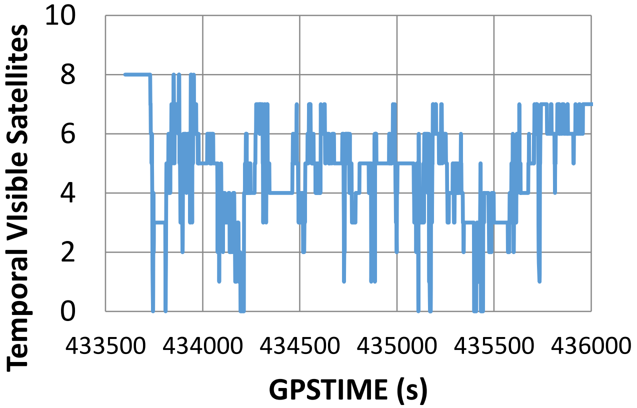
Car tracks and satellite visibility



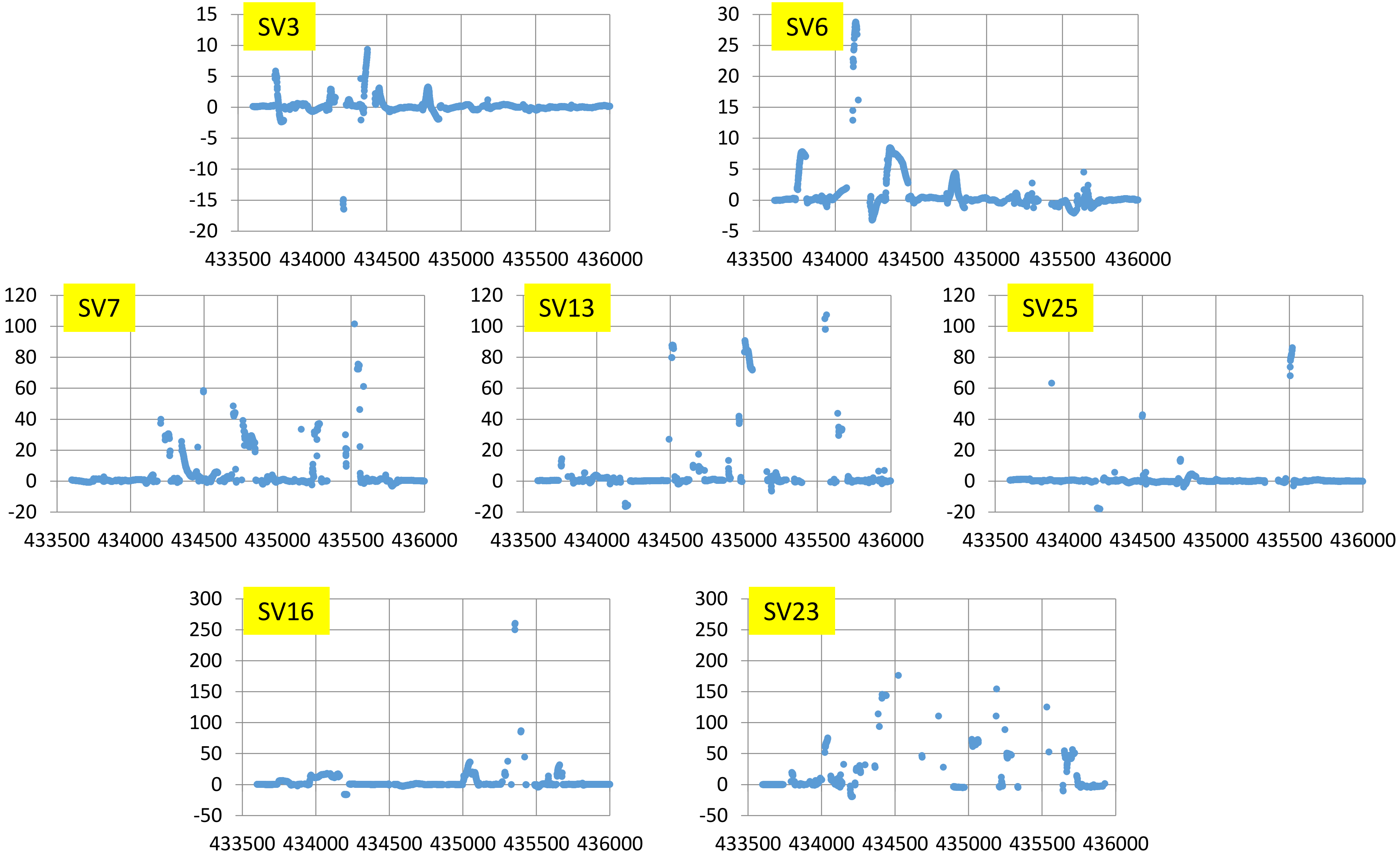
200m

Car Tracks by **POSLV**

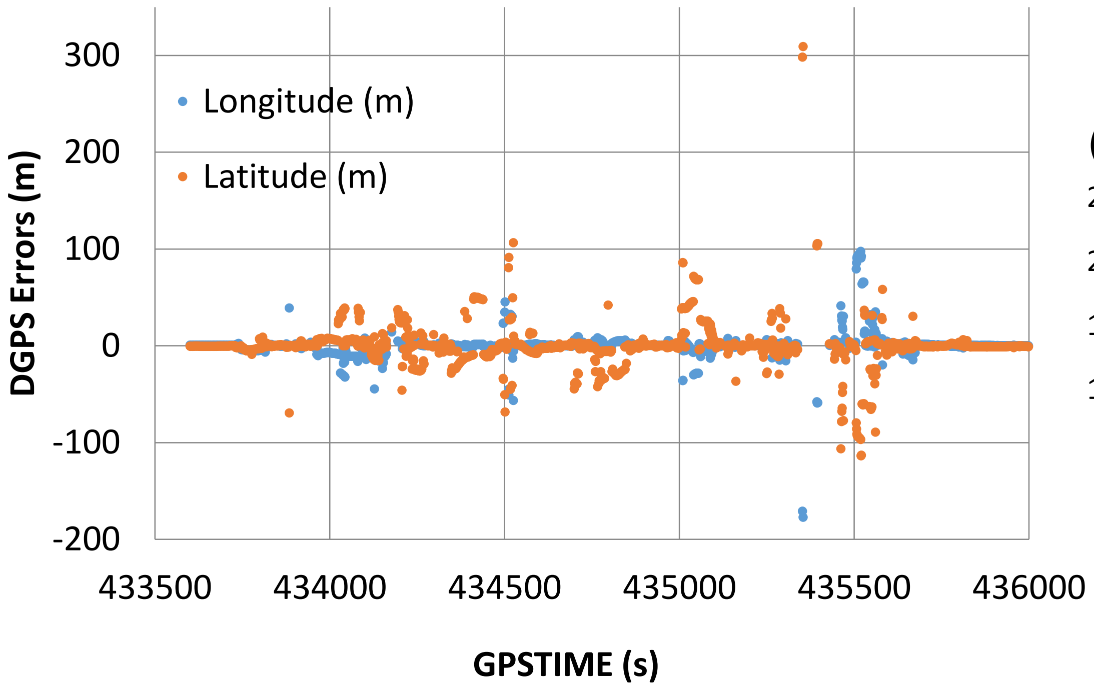


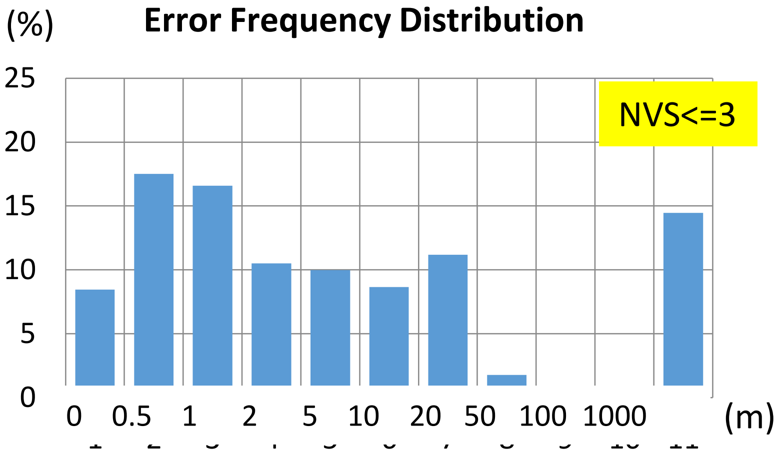


Temporal Multipath Errors by Our Proposed Method



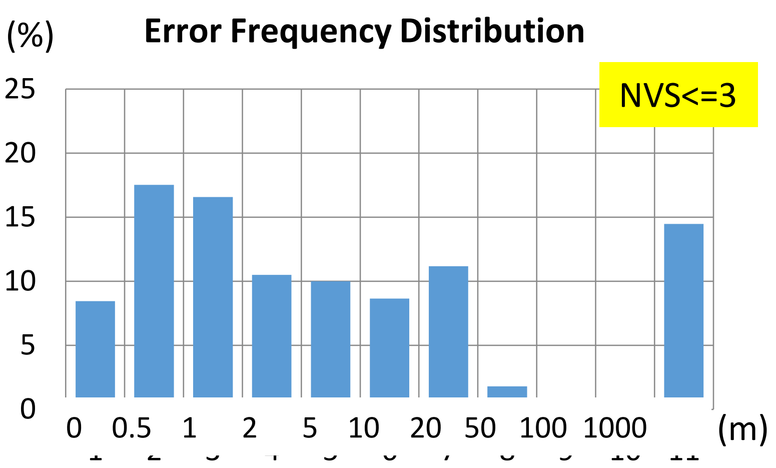
DGPS Errors Analysis

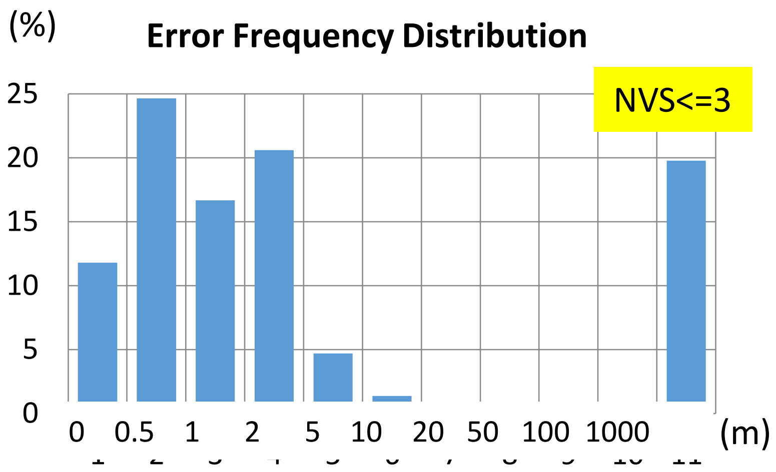




Horizontal (1σ) : 23.63m

Bad Satellite Rejection (MP[prn] ≥ 2.0m rejection)





- The percentage within 1m error: 26.0%→36.5% (56.3%)
- The percentage within 5m error: 53.0%→73.7% (93.5%)

( ) means disregarding the case of “NVS<=3”

Horizontal (1σ) 23.63m → 4.58m

Single Epoch RTK

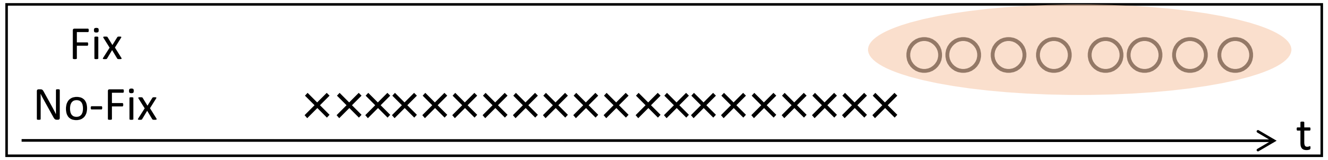
	FIX Rate (Ratio>=3.0)	Wrong Fix (>0.1m*HDOP)	NVS>=4 (Epochs)
Normal RTK	41.7%	2.1%	9808/12265
Normal RTK + MP rejection (2.0m)	50.9%	1.7%	9213/12265
Normal RTK + MP rejection (1.0m)	57.5%	1.8%	8626/12265

Screening for Wrong Fix

(Case : Normal RTK+ MP rejection(1.0m))

Wrong Fix (>0.1m*HDOP)	Actual Horizontal Errors < 0.5m	Limited Number of Epochs
163 epochs (1.8%)	100 epochs	63 epochs

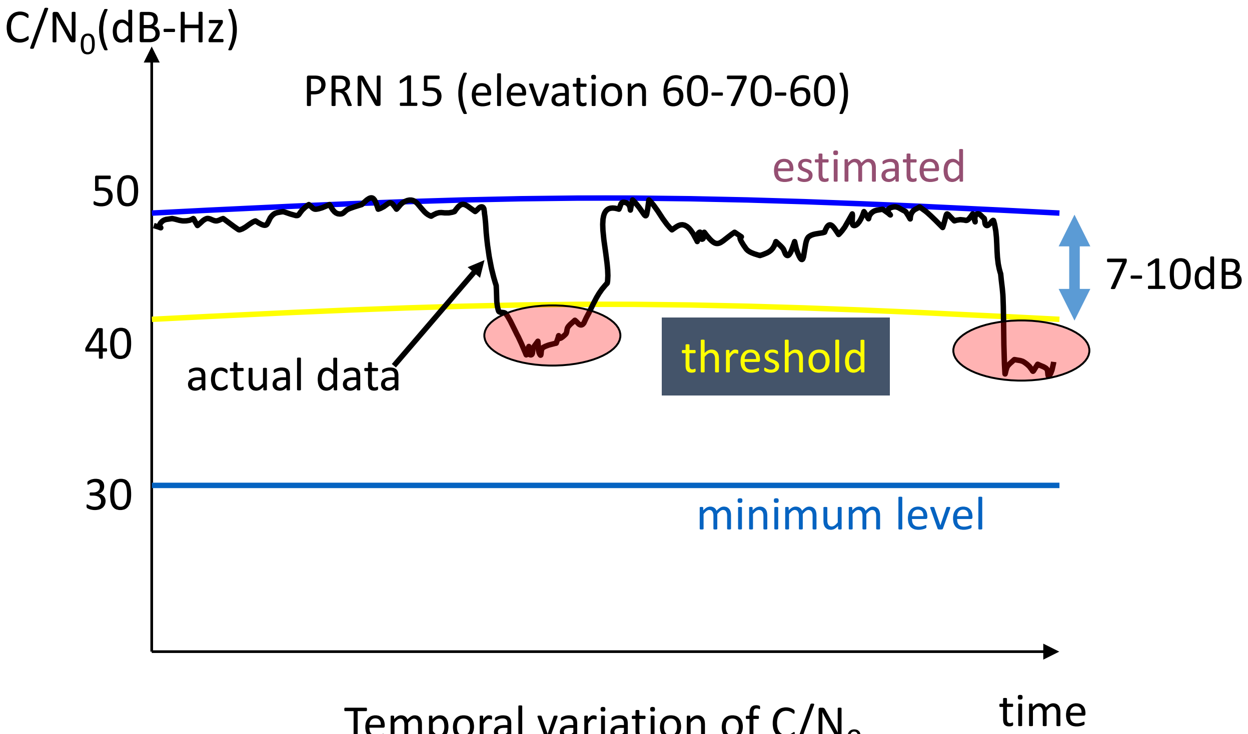
3 Events	NVS is 4 (minimum)	HDOP > 10.0 (bad HDOP)	Return after long No-Fix (10sec)
63 epochs	59 epochs	38 epochs	29 epochs



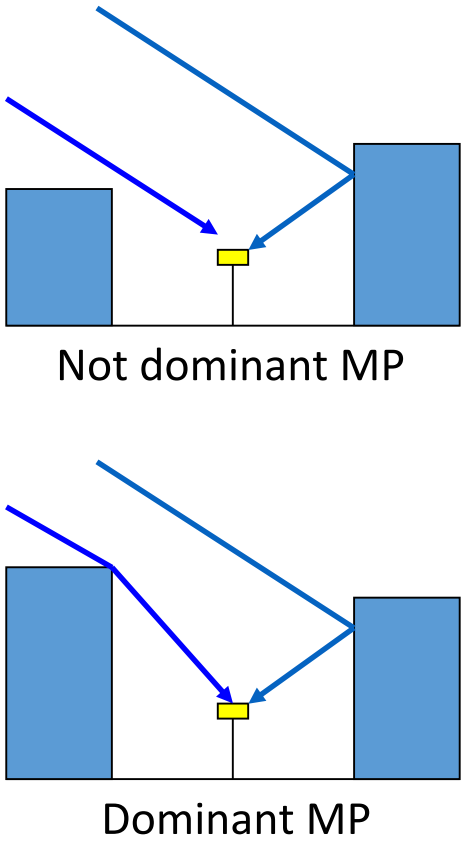
No epochs are not the case with the above 3 events !

Detecting dominant multipath signal
(presented in ION 2005, kubo et al.)

- Detection method is very simple



Temporal variation of C/N_0



Single Epoch RTK in the same manner

	FIX Rate (Ratio>=3.0)	Wrong Fix (>0.1m*HDOP)	NVS>=4 (Epochs)
Normal RTK	41.7%	2.1%	9808/12265
Normal RTK + C/N_0 detection (10.0 dB)	47.2%	2.5%	9510/12265
Normal RTK + C/N_0 detection (7.0 dB)	53.3%	1.8%	8978/12265
Normal RTK + C/N_0 detection **(5.0 dB)**	55.5%	1.7%	8682/12265