Several Research Topics at GNSS lab. (TUMSAT)

Online meeting at Shanghai Astronomical Observatory
3/22/2024
Nobuaki Kubo (TUMSAT)

University and Laboratory

- **T**okyo **U**niversity of **M**arine **S**cience **a**nd **T**echnology
- Marine Technology and Marine Science
- Information and communication engineering laboratory (GPS/GNSS lab.)
- Staff 1 (2), Docter 2, Master 8, Undergraduates 6

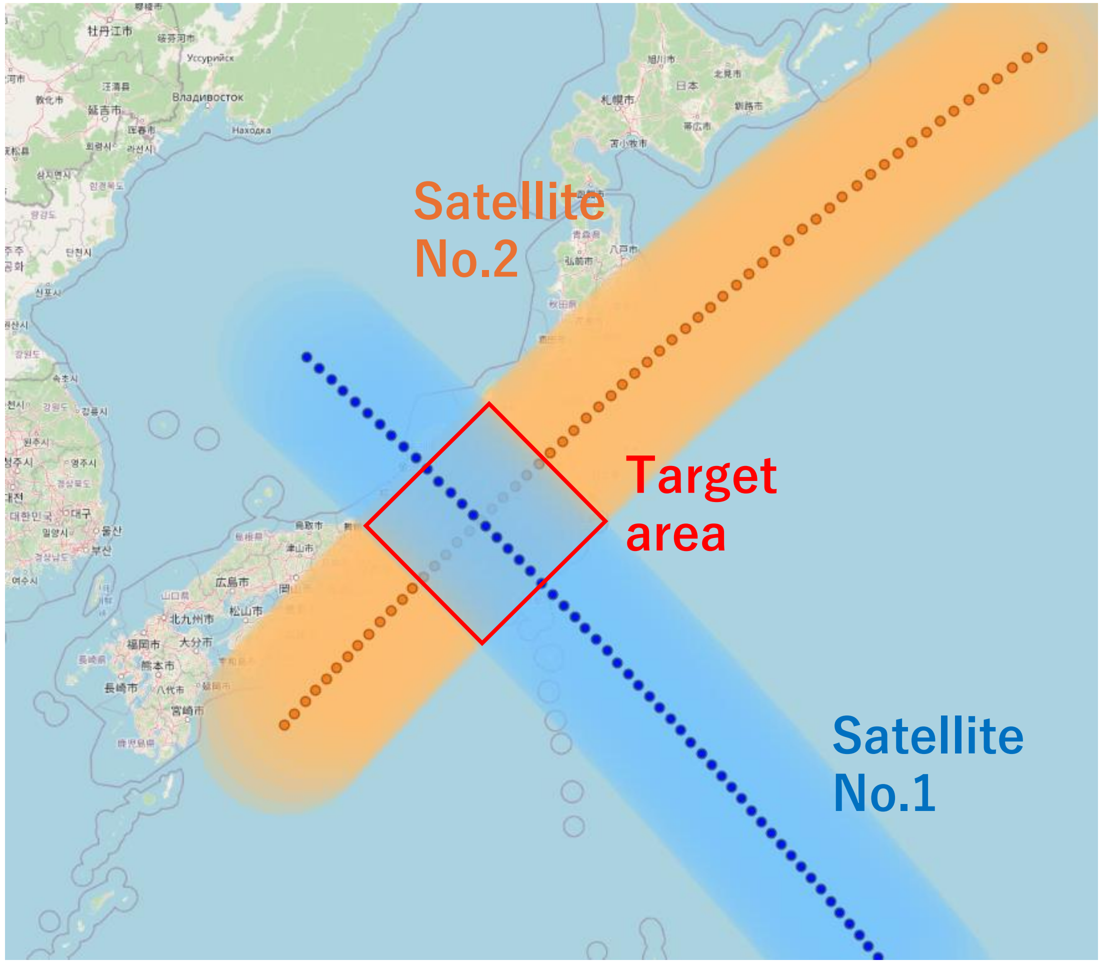


Topics

1. RF signal transmitter location by LEO satellite using TDOA and FOA method
2. Improved Initial Integer Ambiguity Resolution When the Sky Visibility is Considerably Masked
3. RTK-GNSS with Smartphone in Moving Vehicles
4. Static and Kinematic Test Results using PPP/CLAS/SLAS Correction Service through QZSS
5. A New Approach of GNSS Multipath Detection using the Guard time of Satellite Based on C/N_0
6. Modified RTKLIB for Kinematic Urban Condition
7. RTK-GNSS performance prediction

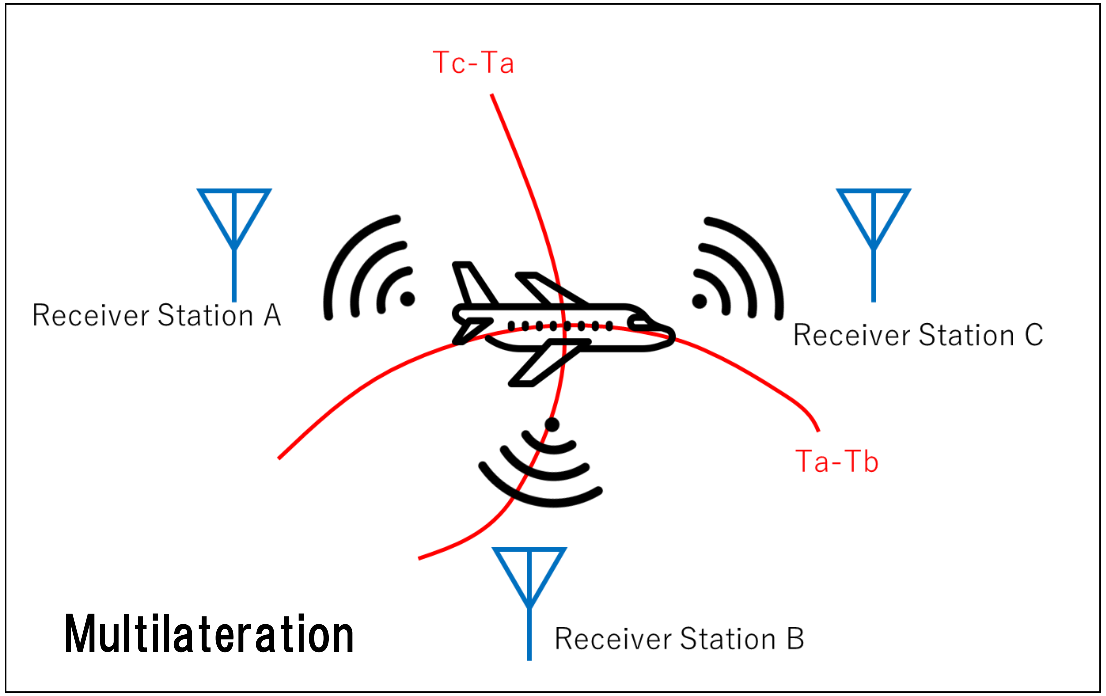
Satellite orbit for TDOA/FOA

- We simulated satellite orbit to receive LPWA signal.
- At least two satellites are required, we used two Starlink orbit which cover Kanto Area in Japan.
- Altitude of the satellite is 550km.
- We calculated satellite position using SGP4 model from TLE information.
- We assumed there is GNSS on the satellite and its position accuracy is approximately 5m.

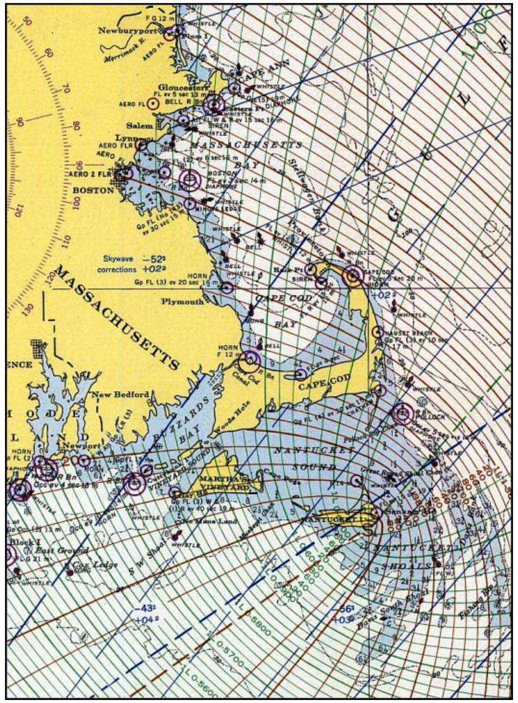


TDOA method

- In TDOA method, a hyperbola is drawn from transmit signal arrival time difference between 2 stations.
- If there is 3 station, you can make 2 hyperbola and determine transmitter position.
- TDOA method is used as LORAN-C and Multilateration.



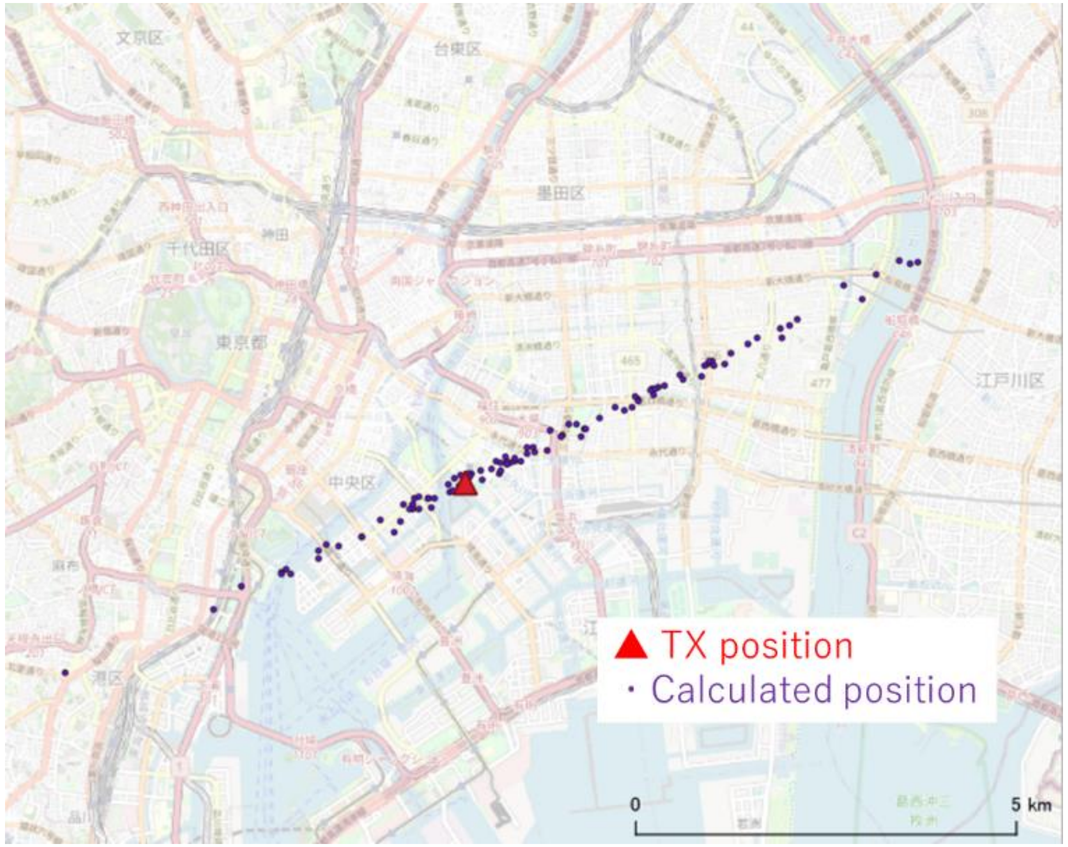
Multilateration


LORAN-C chart

Evaluation of TDOA

- We simulated 3 observation interval.
- If observation interval is short, positioning accuracy will decline.
- When observation interval is 15 sec, horizontal RMS error is 2.5km

	5 sec interval		10 sec interval		15 sec interval	
	2D error	3D error	2D error	3D error	2D error	3D error
AVG[m]	13440	44762	3403	11716	1942	6764
STD[m]	12592	41534	2856	9833	1608	5612
RMS[m]	18417	61063	4443	15296	2522	8789



Horizontal Plot of 15 sec interval

FOA method

- FOA need at least two satellites and several times observation of Frequency of Arrival.
- FOA can calculate transmitter position without knowing its frequency.
- FOA and position, velocity of satellite are required.
- $\boldsymbol{x}$ was obtained by weighted least-squares method.

$$z(t_k) = h(t_k) + v(t_k)$$

$$h(t_k) = f_c + \frac{1}{\lambda}\frac{\left(\mathbf{v}_U(t_k)\right)^T\left(\mathbf{p}_T - \mathbf{p}_U(t_k)\right)}{\|\mathbf{p}_T - \mathbf{p}_U(t_k)\|}$$

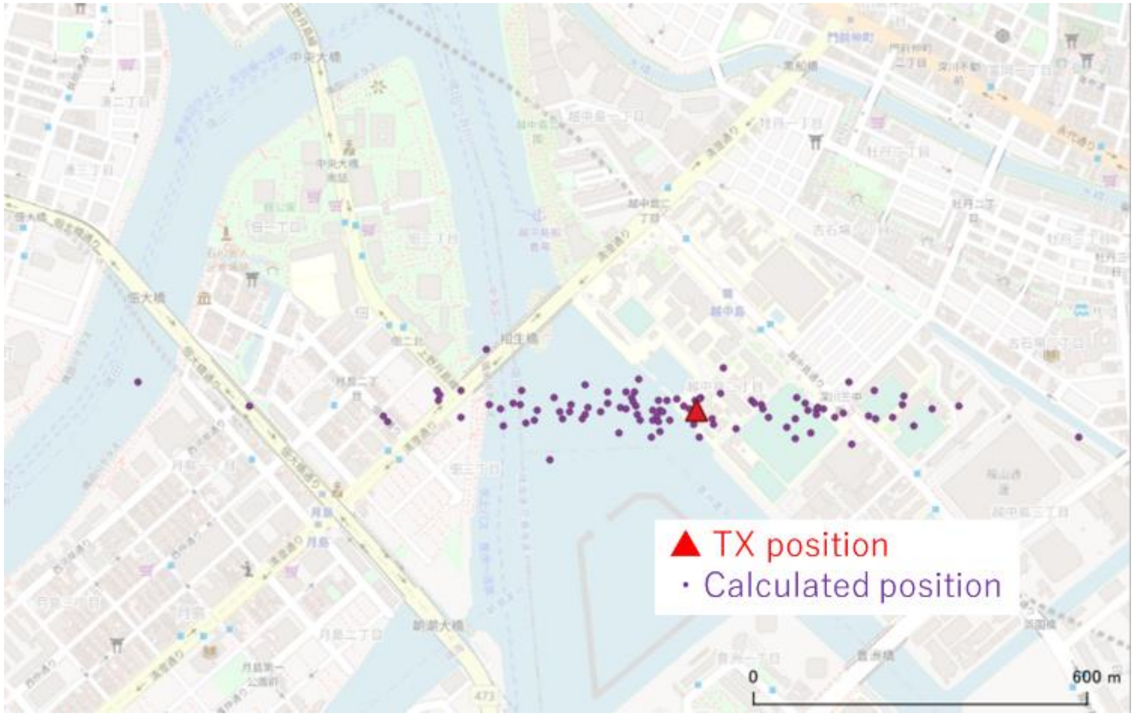
$$\boldsymbol{x} \doteq \begin{pmatrix} \mathbf{p}_T \\ f_c \end{pmatrix}$$

k : Observation number (0~n)
$z(t_k)$：Measured FOA（Frequency Of Arrival）
$h(t_k)$：True FOA
$v(t_k)$：Measurement error by thermal noise
f_c：Transmit frequency
λ：Length of wave (=c/fc)
$\mathbf{p}_T$：xyz position of transmitter
$\mathbf{p}_U(t_k)$：xyz position of satellite
$\mathbf{v}_U(t_k)$：xyz velocity of satellite

Takeshi Amishima. Theoretical FOA Based Geolocation Accuracy by Single Moving Platform Considering Orbital Error. IEICE Transactions on Communications, Vol.J106-B, No.2, pp.88-100, 2023

Evaluation of FOA

- We calculated positioning accuracy of 6 pattern.
- The higher the frequency of the transmitter signal, the higher the accuracy.
- The higher the thermal noise, the lower the accuracy.
- When thermal noise is 2Hz, horizontal RMS error was 300m in 1GHz.

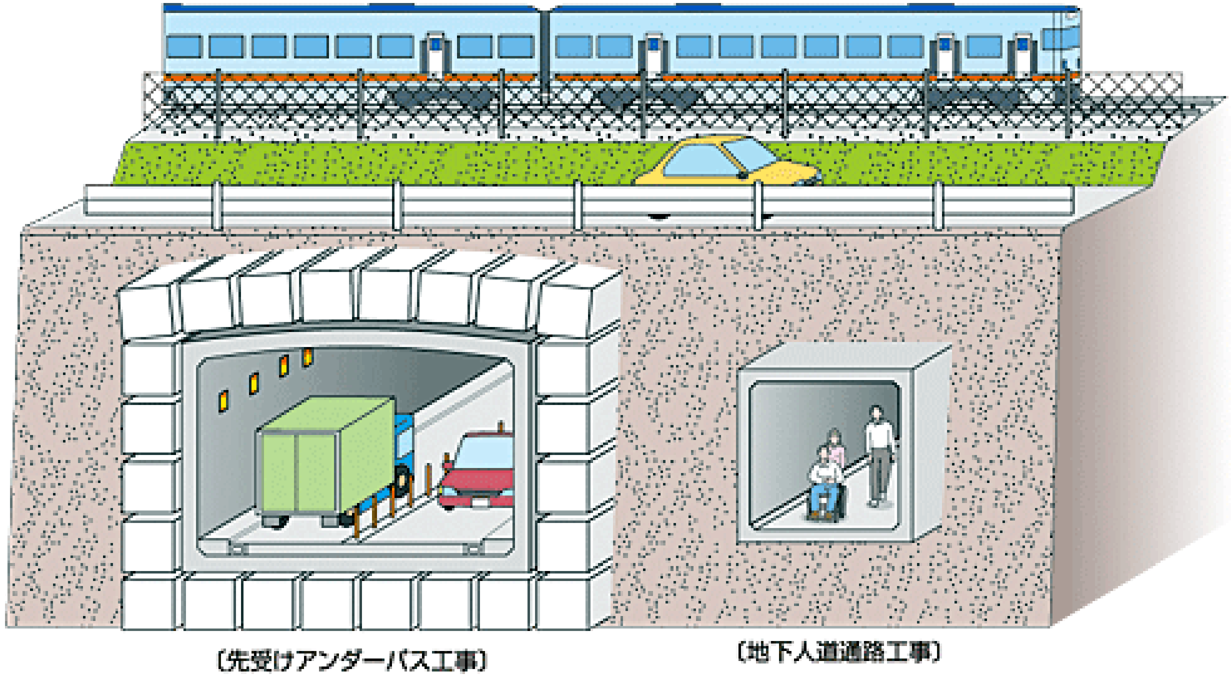


Horizontal Plot of 1GHz Tx and 2Hz noise

1 GHz			
FOA thermal noise	2D RMS Error[m]	3D RMS Error[m]	Frequency Estimation Error[Hz]
2 Hz	292	324	8.7
10 Hz	1652	1833	49.2
50 Hz	7820	8941	238.1

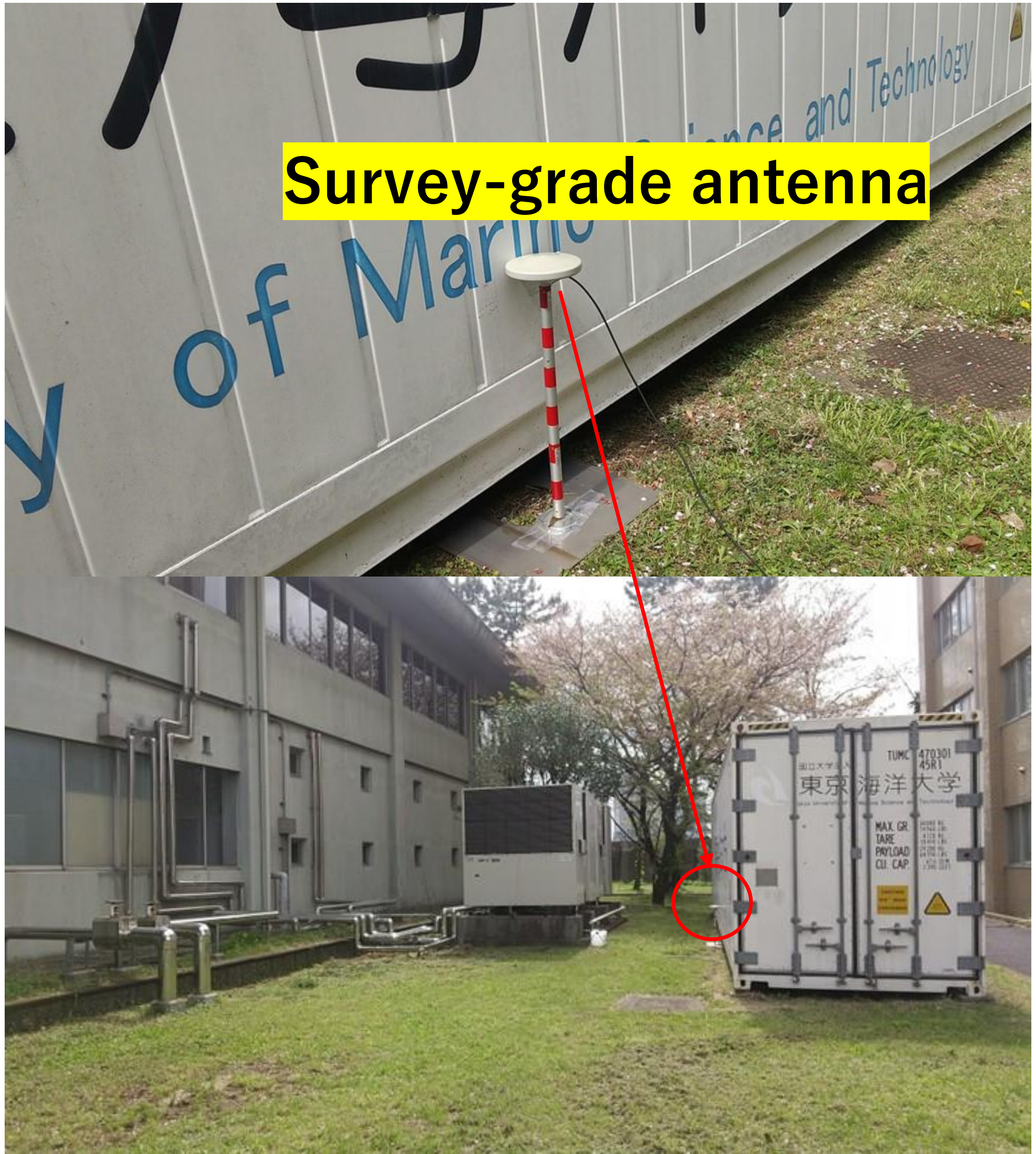
5 GHz			
FOA thermal noise	2D RMS Error[m]	3D RMS Error[m]	Frequency Estimation Error[Hz]
2 Hz	117	131	17.8
10 Hz	331	364	49.4
50 Hz	1828	2018	277.9

Monitoring of small lateral movement in challenging environments



1. Crossing passageway on highway embankment section
2. Under-track corridor as a solution for unopened railroad crossings
3. Underground crossing passages at intersections with high traffic volumes

Commercial receivers and survey grade antenna



Time : 4/6/2023 3:00-7:00 (UTC)
Base stations were set as same receiver respectively.

Low-cost

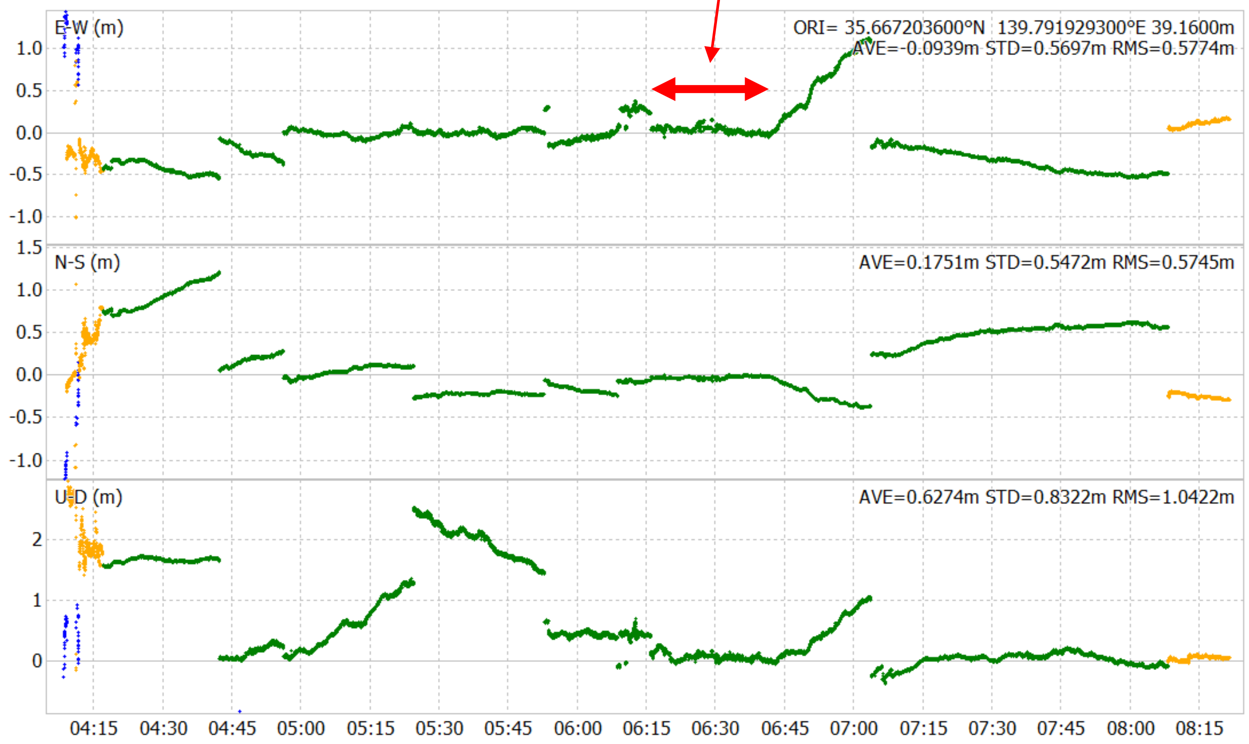
Survey-grade

3 types of positions were evaluated simultaneously in real time.

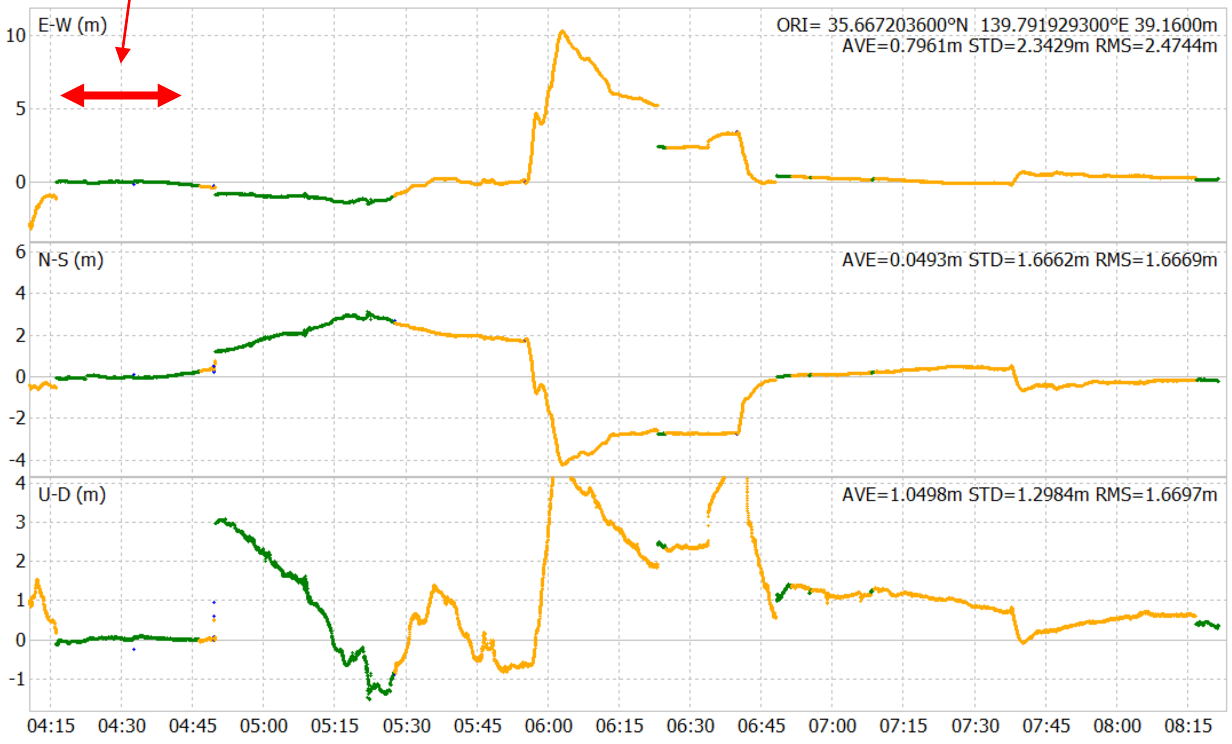
1. RTK engine using low-cost receiver
2. RTK engine using survey-grade receiver
3. Our engine using low-cost receiver
   (**modified RTKNAVI in Note PC**)

Two commercial receiver's RTK engine

Approx. 25 min. were within 10 cm in ENU compared to true positions.



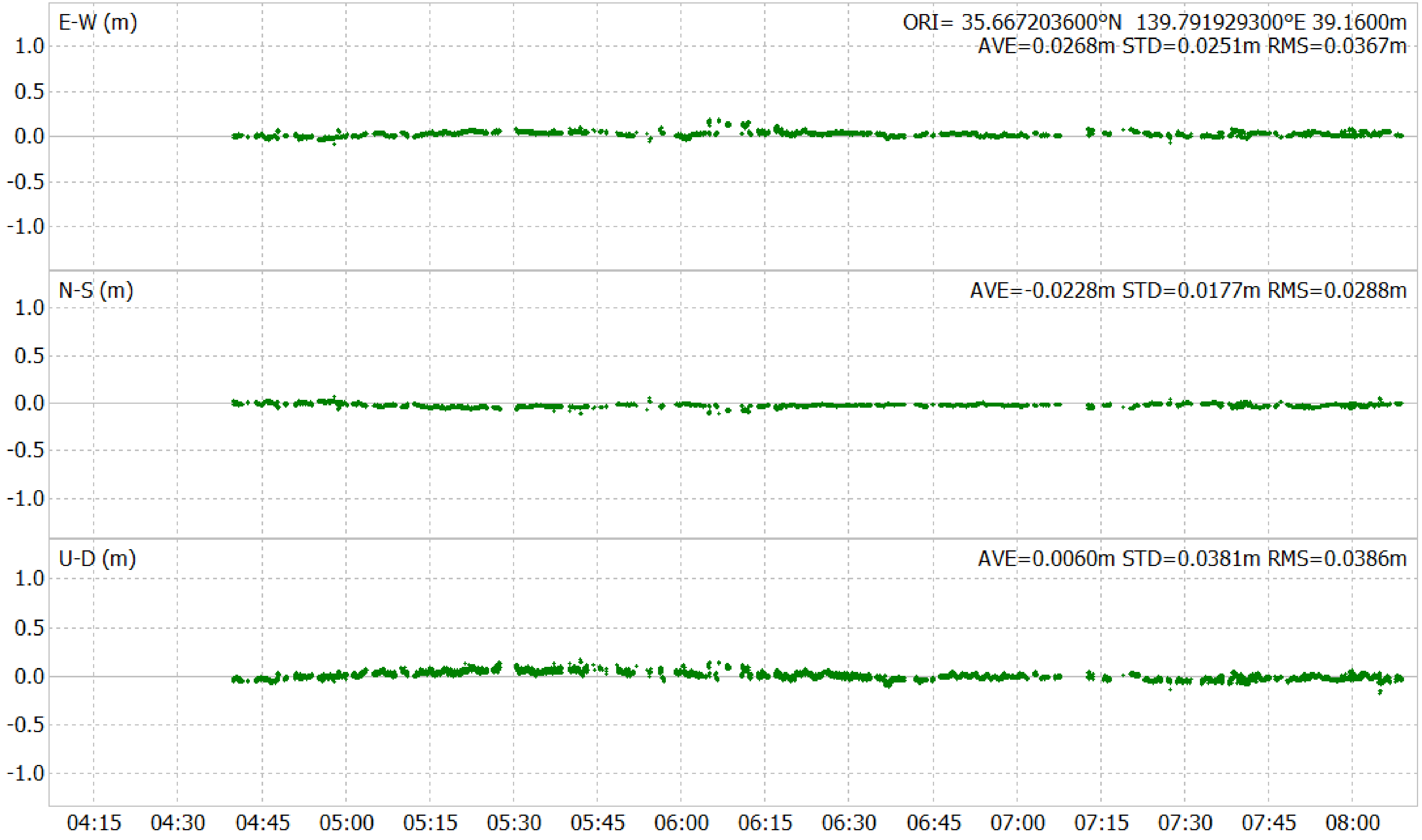
Survey-grade receiver's engine



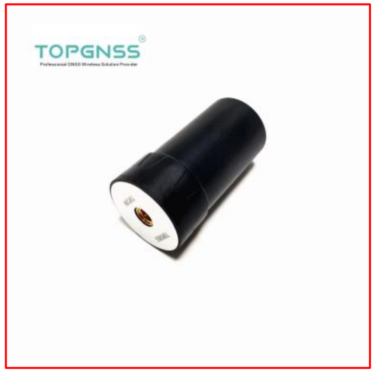
Low-cost receiver's engine

Big issue : Many large wrong fixes positions.

Our engine using low-cost receiver

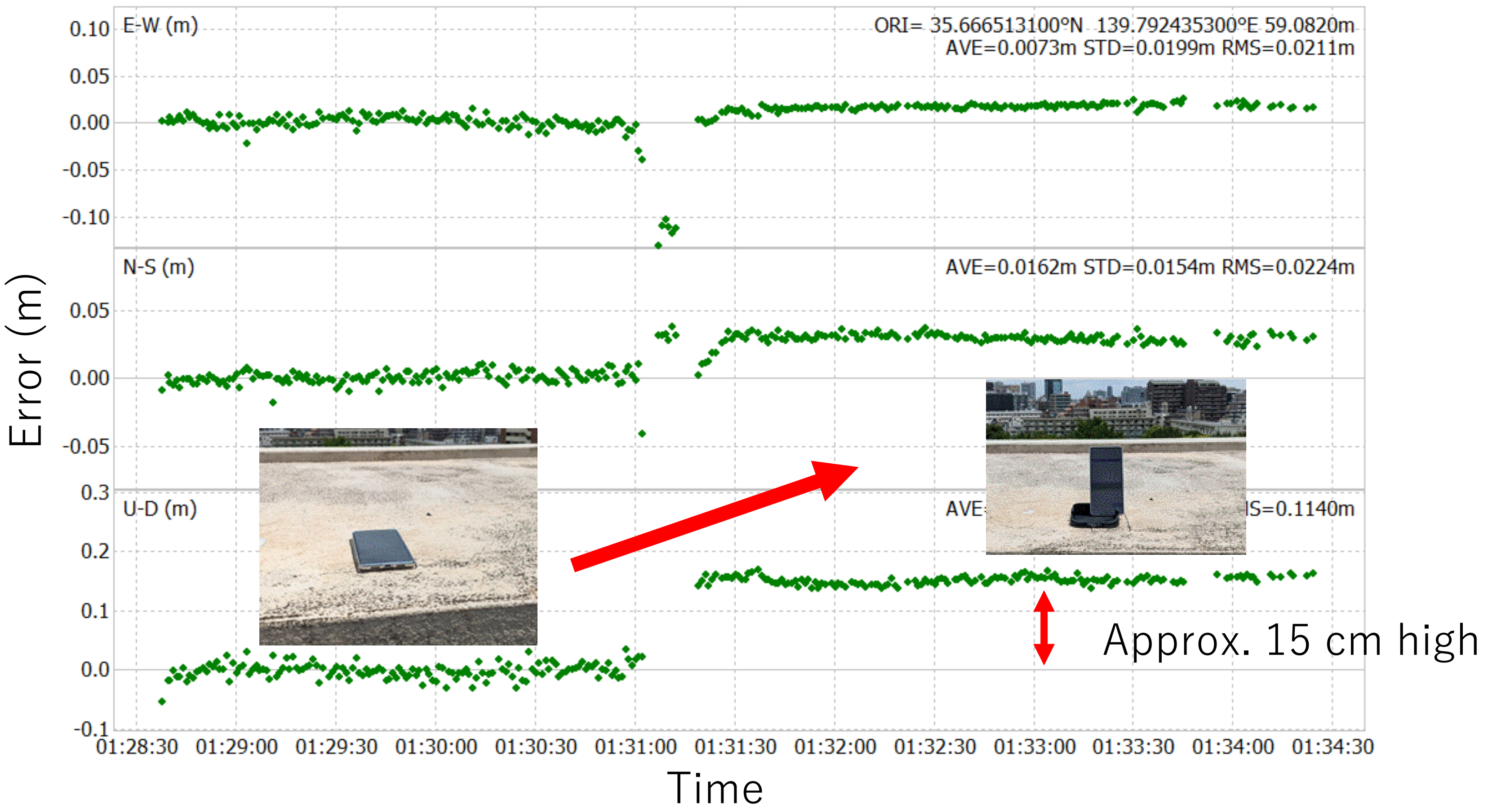


After initial position estimation, most of errors (over 90%) were within 10 cm.



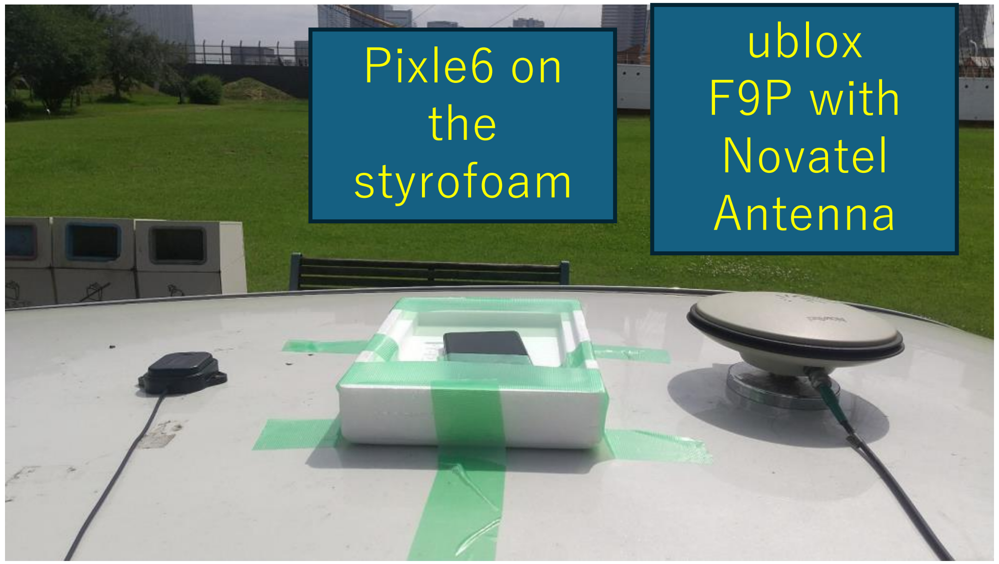
Smartphone RTK testing

RTK-GNSS using Pixel6
(L1, GQEB, 30dBHz, Lab's software)



Kinematic Test (Car)

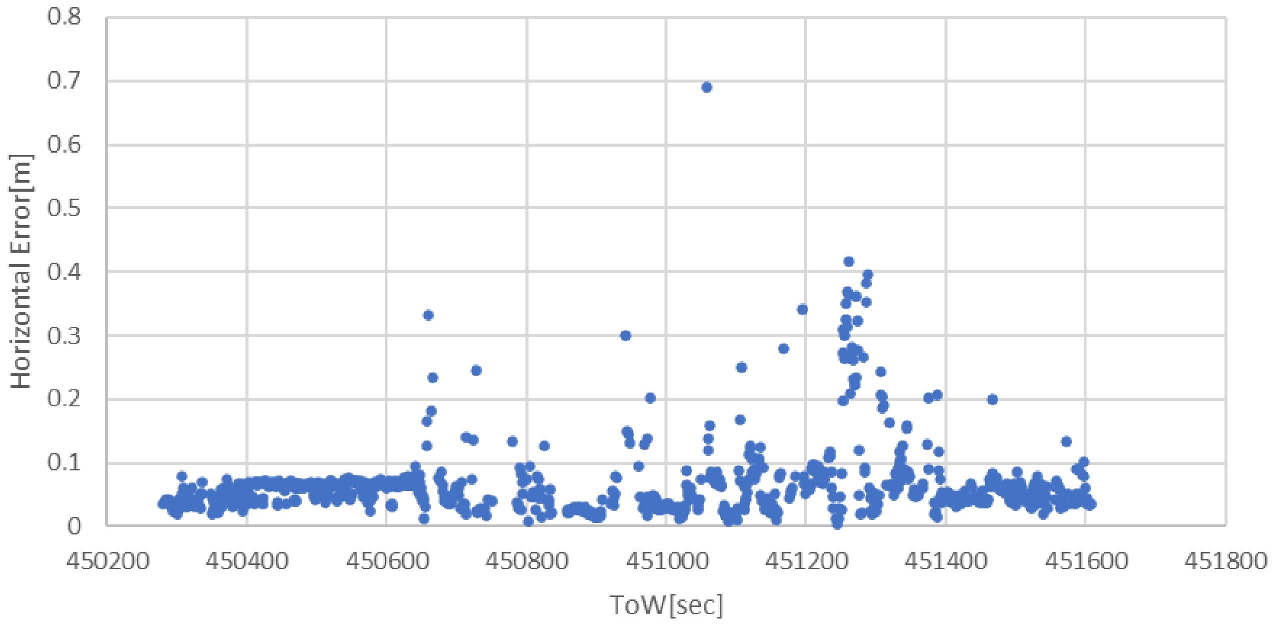
- We conducted the car experiment with pixel6 in middle urban area.
- L1 band, GQEB
- RTK Fix rate was 72.5%
  at CN0>42dBHz



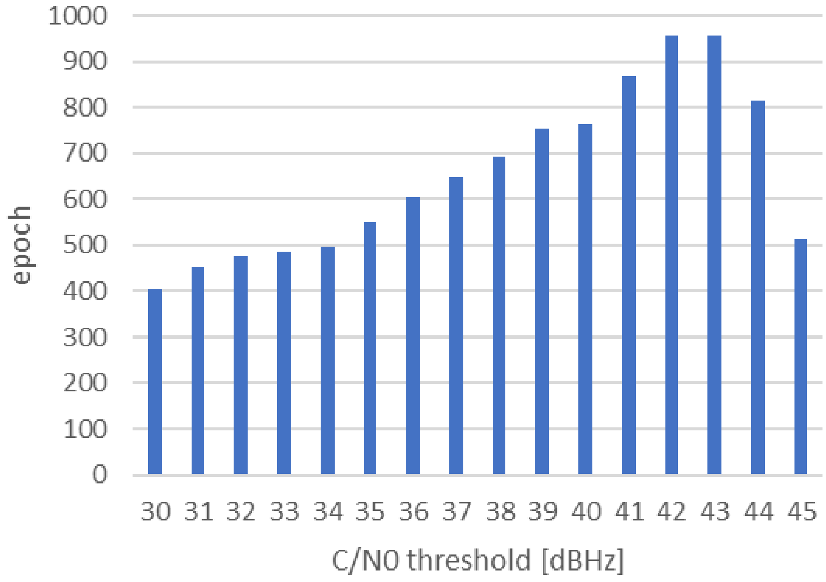
Kinematic Test (Car)

Pixel6 RTK error compared with smartphone true position calculated from F9P RTK result and heading information.

Maximum horizontal error was 70cm and RMS was 8.6cm.

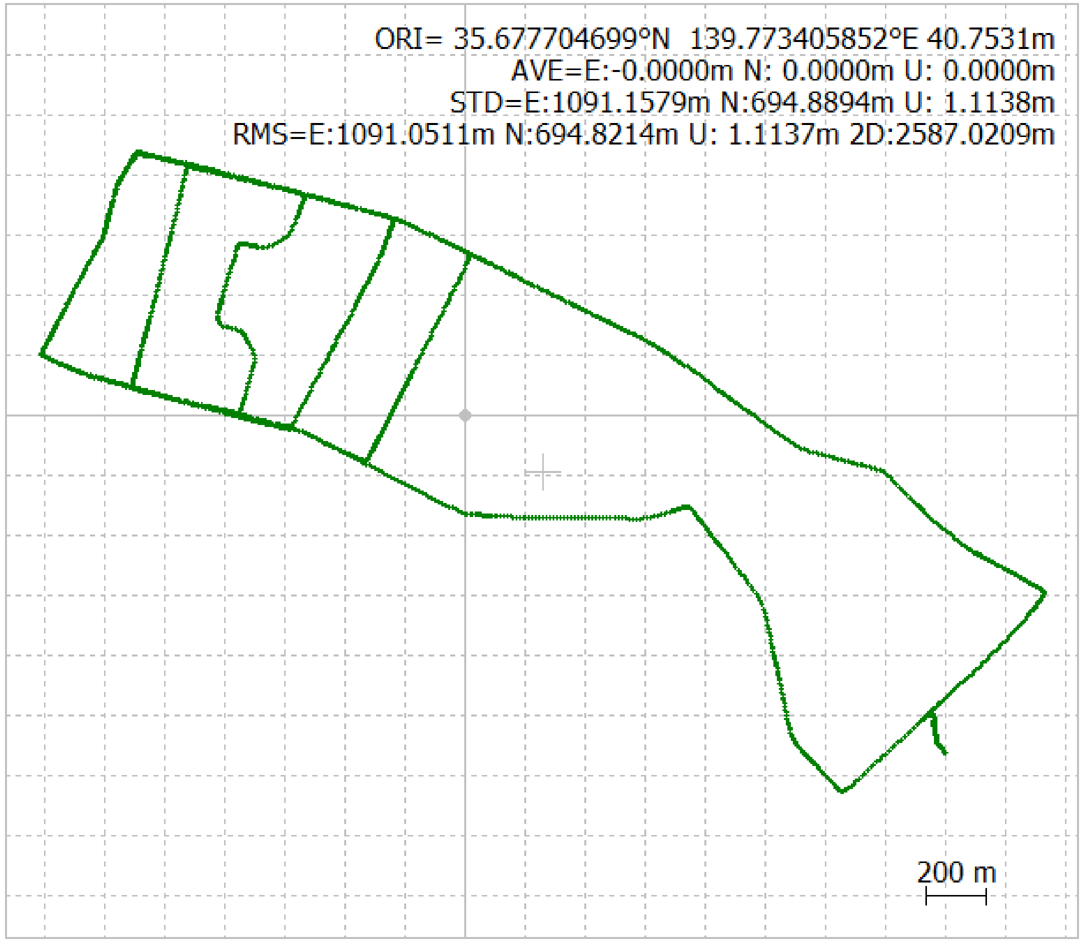


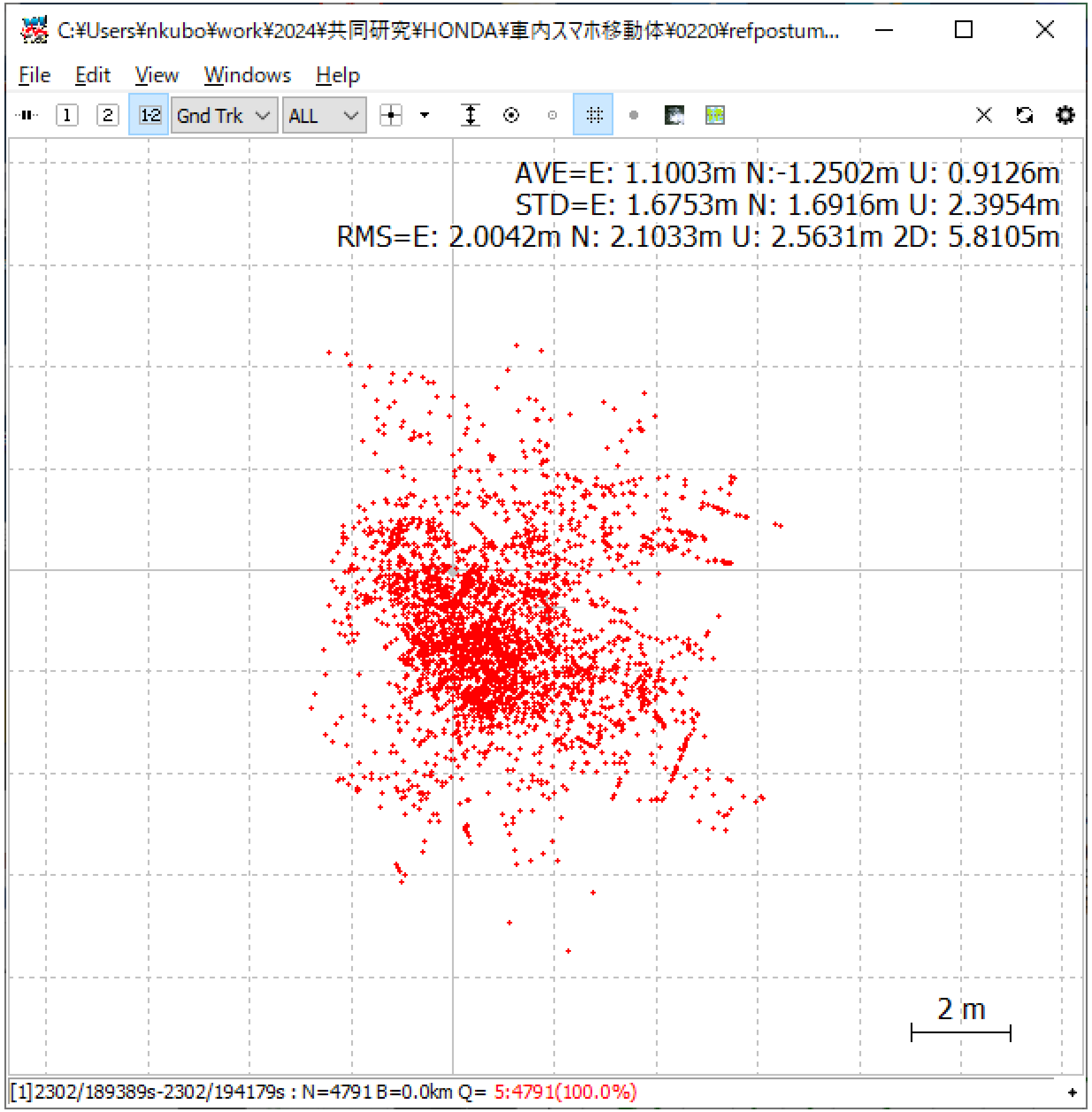
Pixel6 RTK error



RTK Fix epoch

Smartphone's NMEA in dense urban area

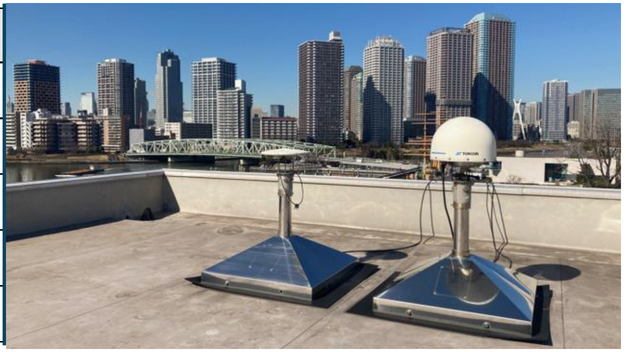




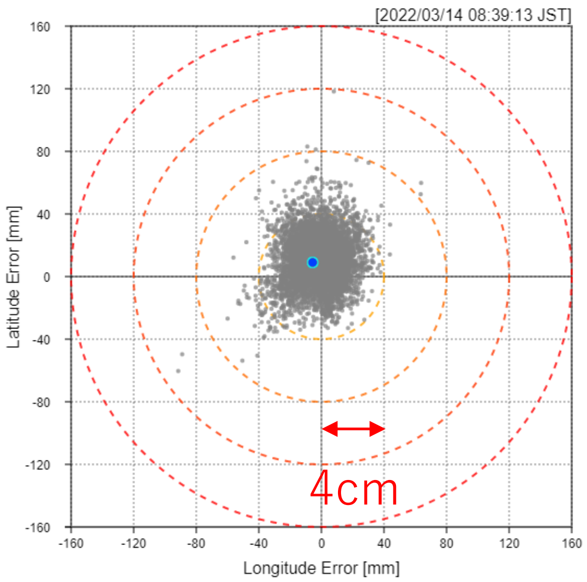
Static test results of CLAS/PPP/SLAS at TUMSAT

- We started the real-time evaluation of CLAS/PPP/SLAS.
- Reference position is determined by some static PPP solutions in ITRF2014.

No.	Label	Port	ID	Date (JST)	Latitude[deg]	Longitude[deg]	Height[m]	N Error[cm]	E Error[cm]	U Error[cm]	Fix type
1	CLAS	10031	POS	2022/03/14 08:38:57	35.66634190	139.79221106	59.819	0.196	-0.294	0.243	1
2	PPP	10032	POS	2022/03/14 08:38:57	35.66634163	139.79221097	59.775	-2.807	-1.140	-4.080	2
3	SLAS	10033	POS	2022/03/14 08:38:57	35.66633131	139.79220029	60.214	-32.646	-13.706	41.700	4
4	RTK	10034	POS	2022/03/14 08:38:57	35.66634026	139.79221121	59.810	-17.988	1.031	-0.620	1
5	SPP	10035	POS	2022/03/14 08:38:57	35.66635381	139.79219544	56.753	217.012	-57.624	-304.400	5

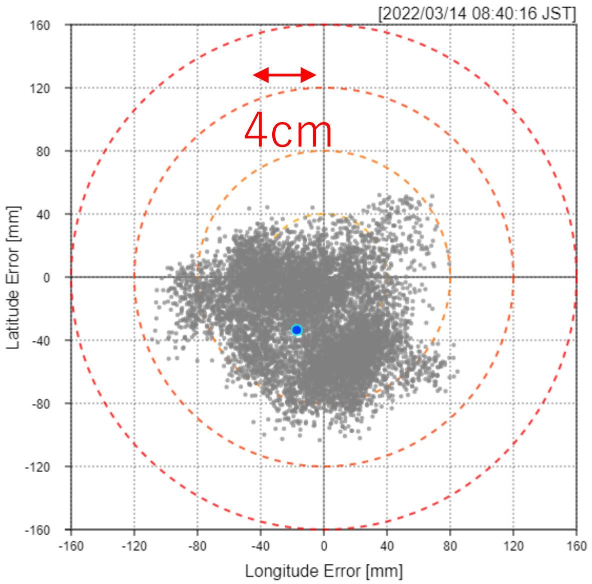


CLAS



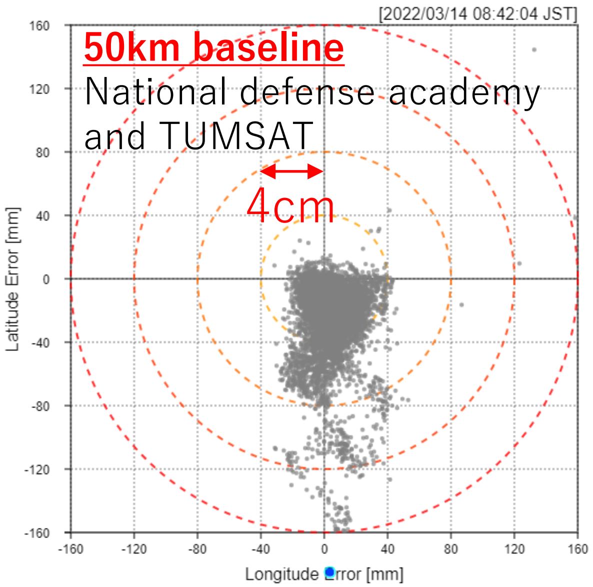
Core
AsteRx4

PPP



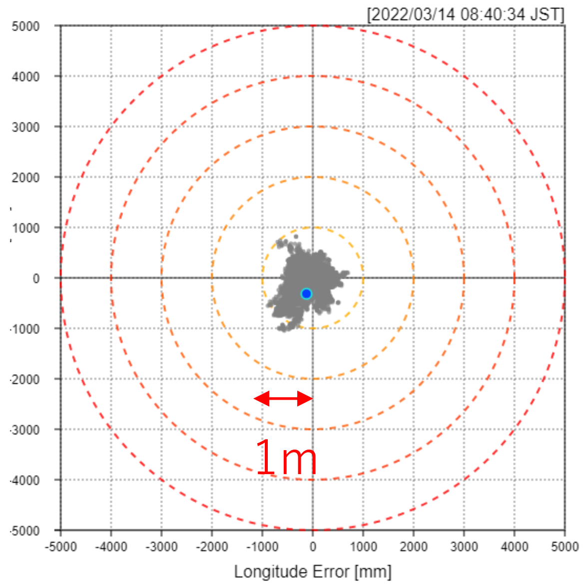
Magellan Systems Japan
MJ-3008-GM4-QZS

RTK



u-blox
F9P

SLAS



Trimble NetR9 ⇨ u-blox F9P

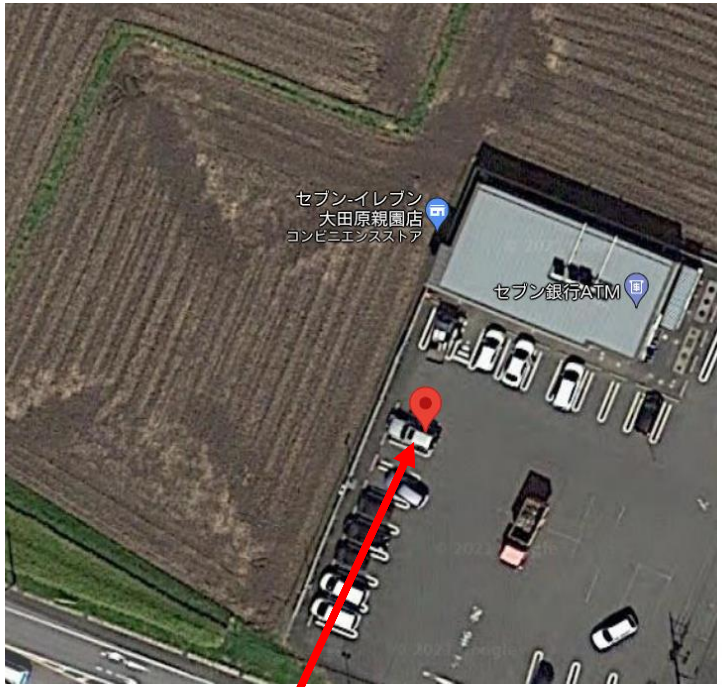
Kinematic test at farmer (Iwaki-san)
CLAS/PPP/SLAS based on RTK

Useful software ! We can see where we plowed.

https://agri-info-design.com/

GNSS LAB Tumsat

Test field (Google)



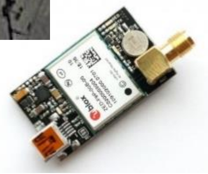
Base station for RTK was set up here.

GPS-703-GGG-HV

Pre-planting soybeans

4 splitter

Lighthouse (PPP)



u-blox F9P(SLAS)

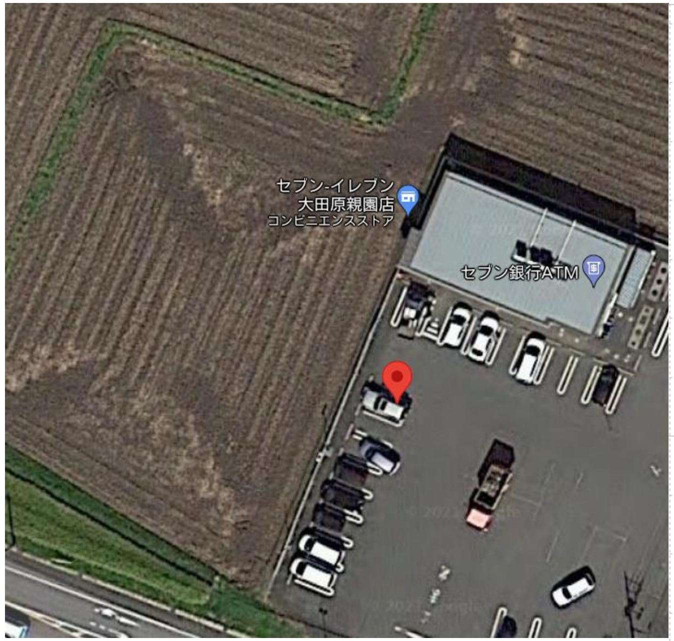
u-blox F9P(RTK)

Core AsteRx4(CLAS)

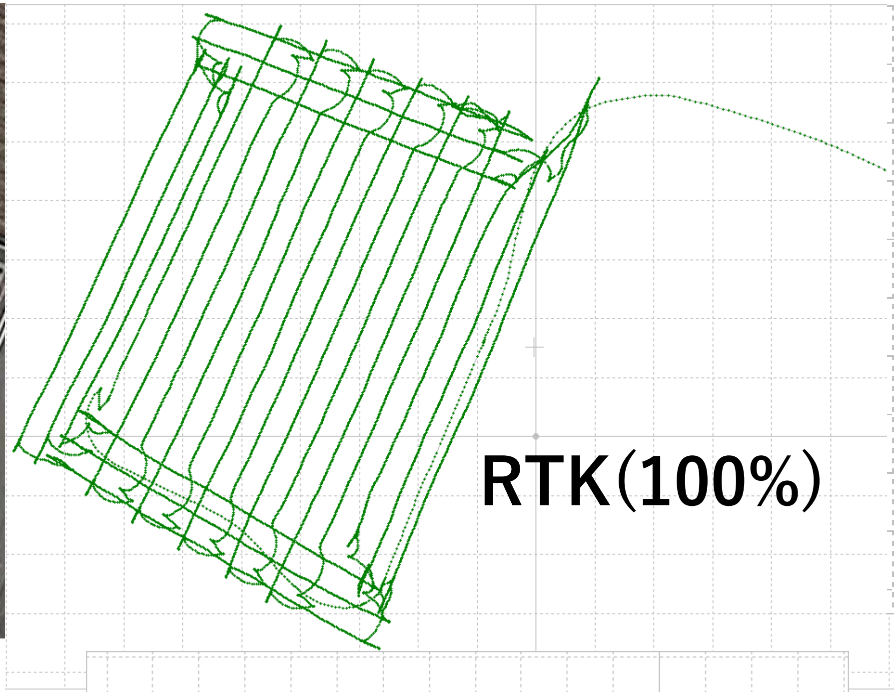
GNSS antenna

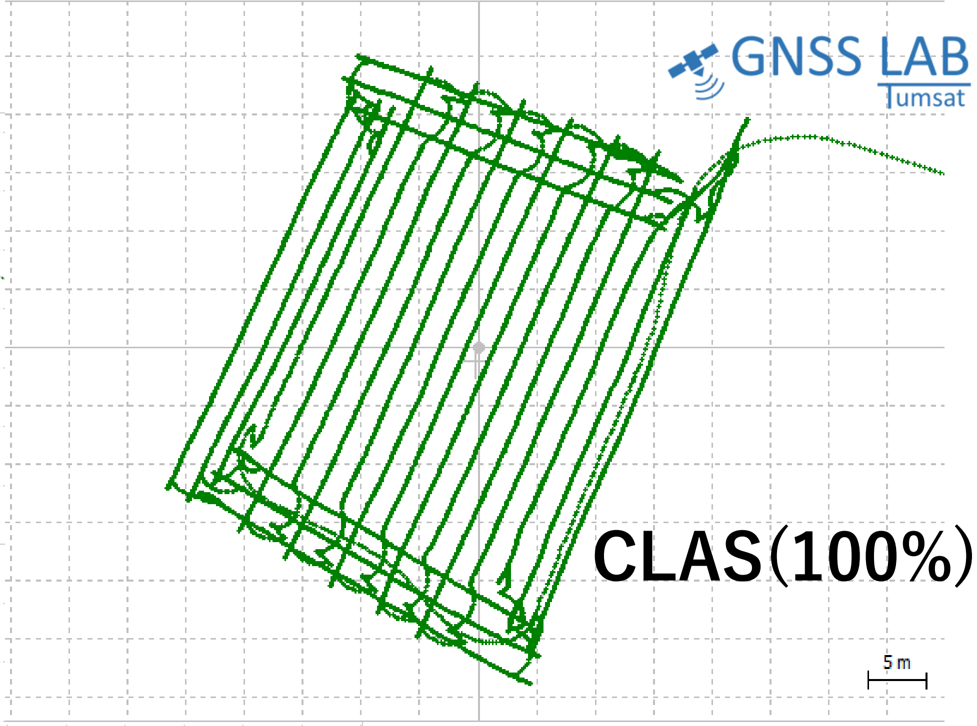
Lidar/Camera

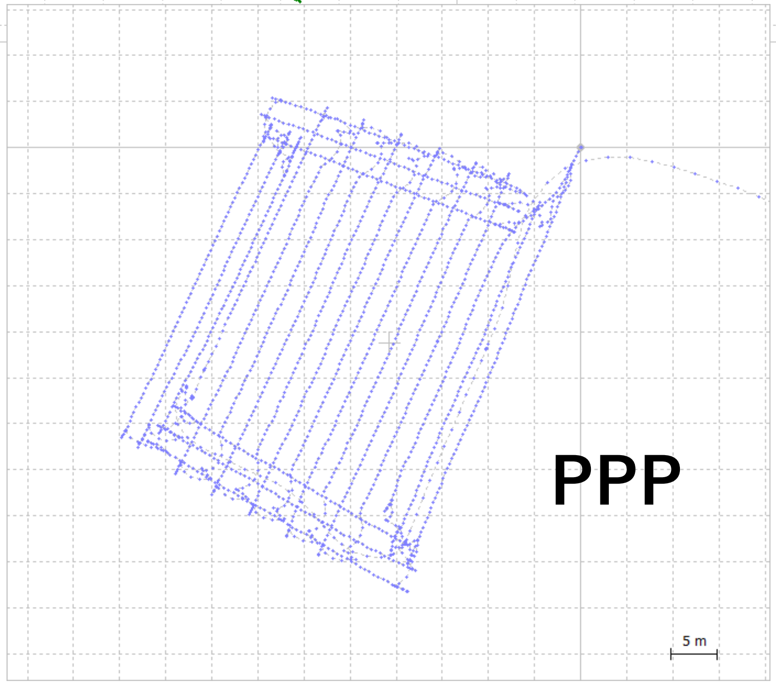
Ground Truck Comparisons

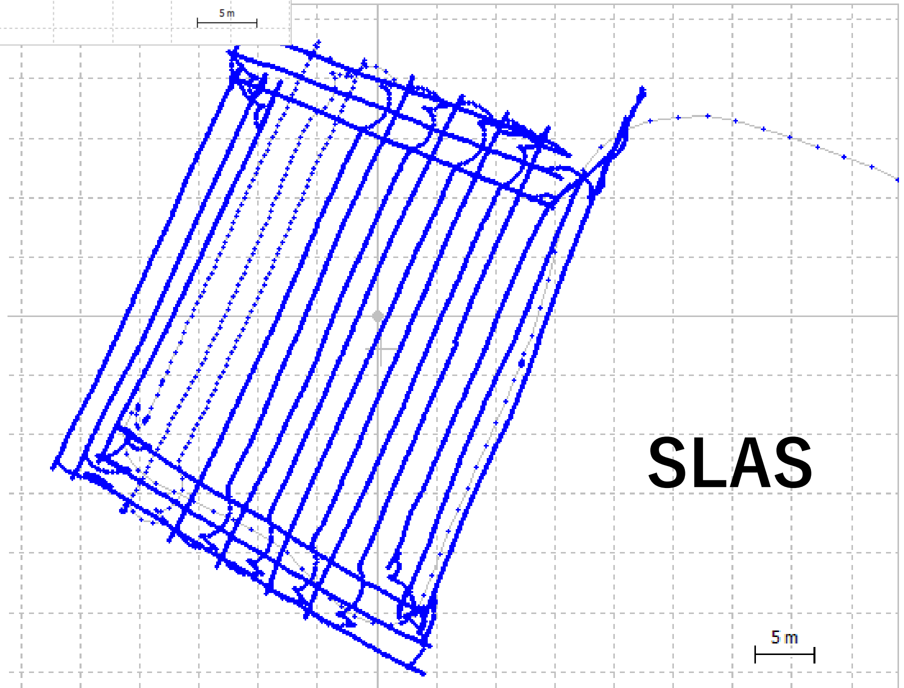


Test field
difficult to compare…

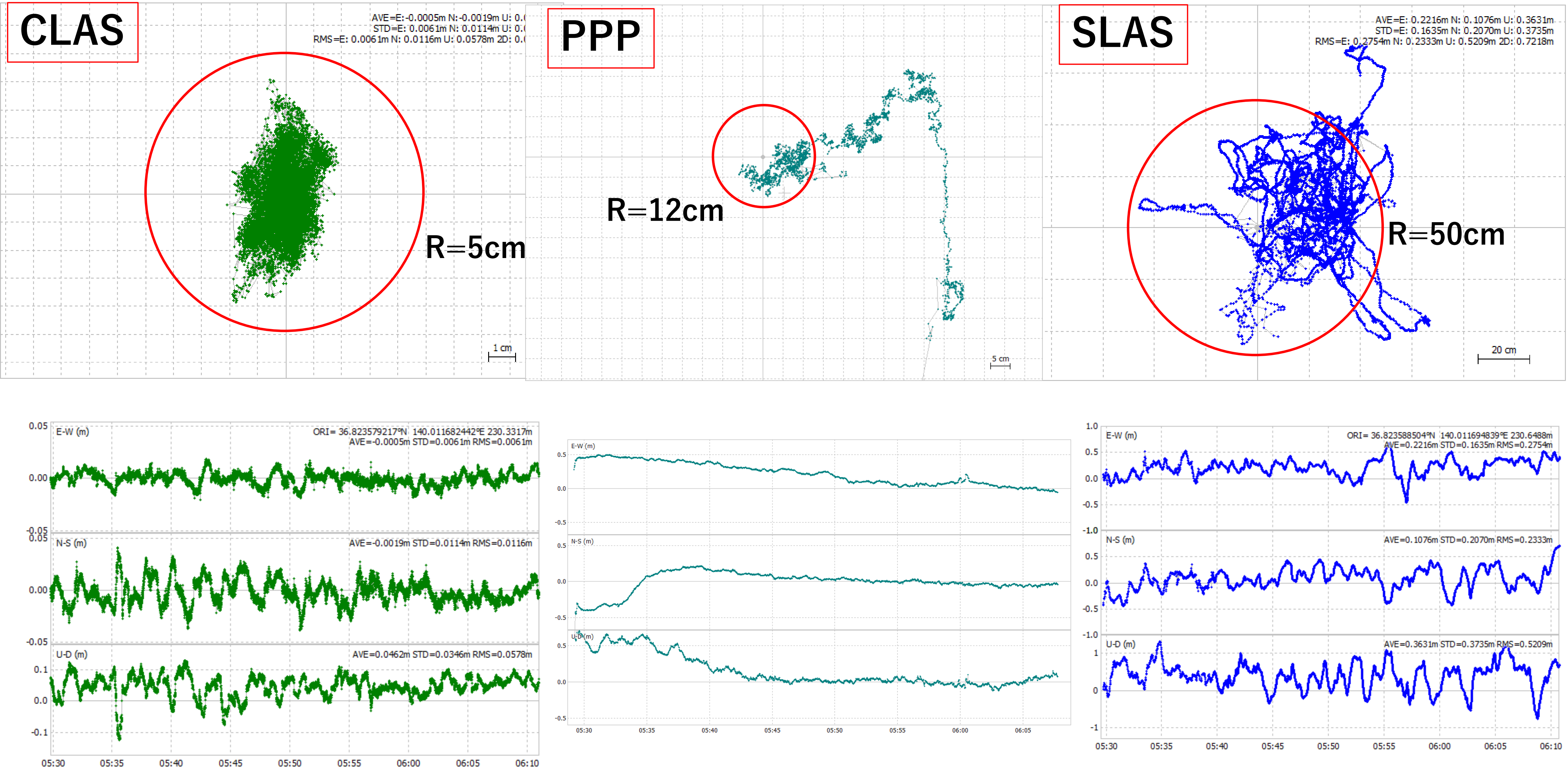






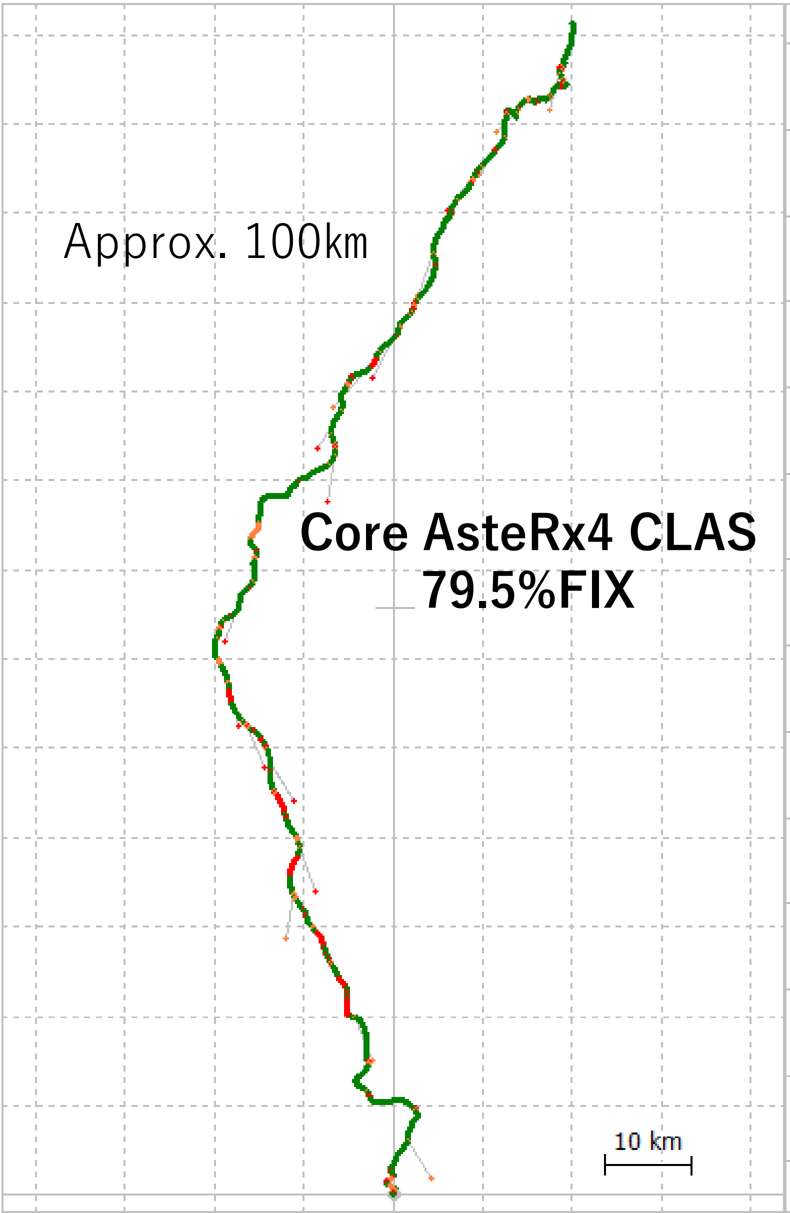


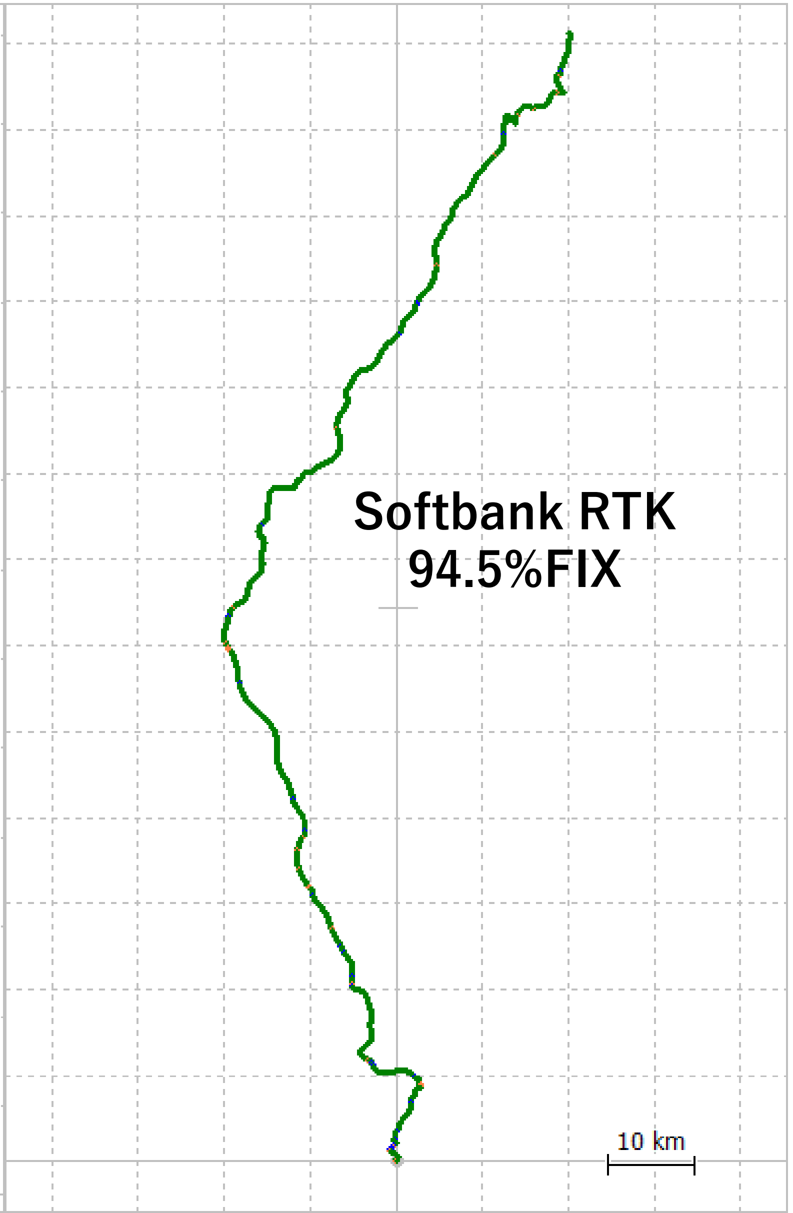
Position Errors for CLAS/PPP/SALS

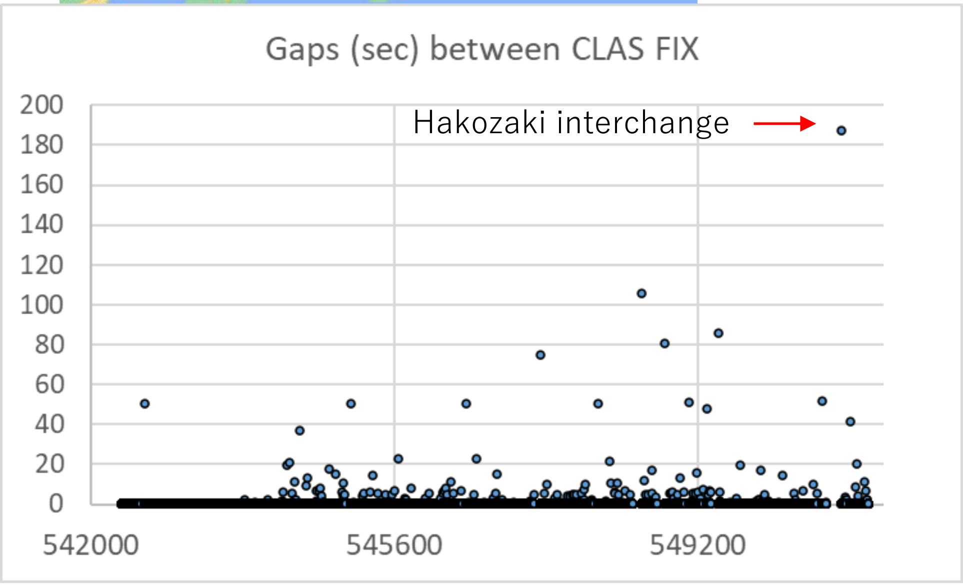


CLAS during 100km expressway

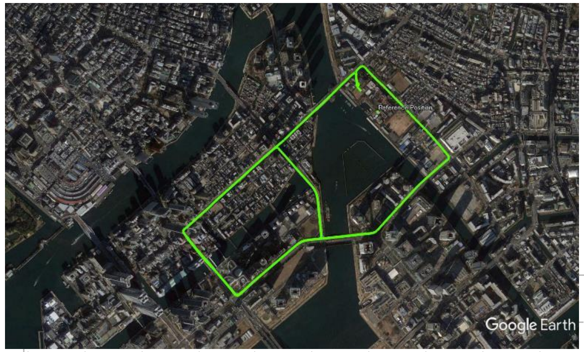
GNSS LAB Tumsat





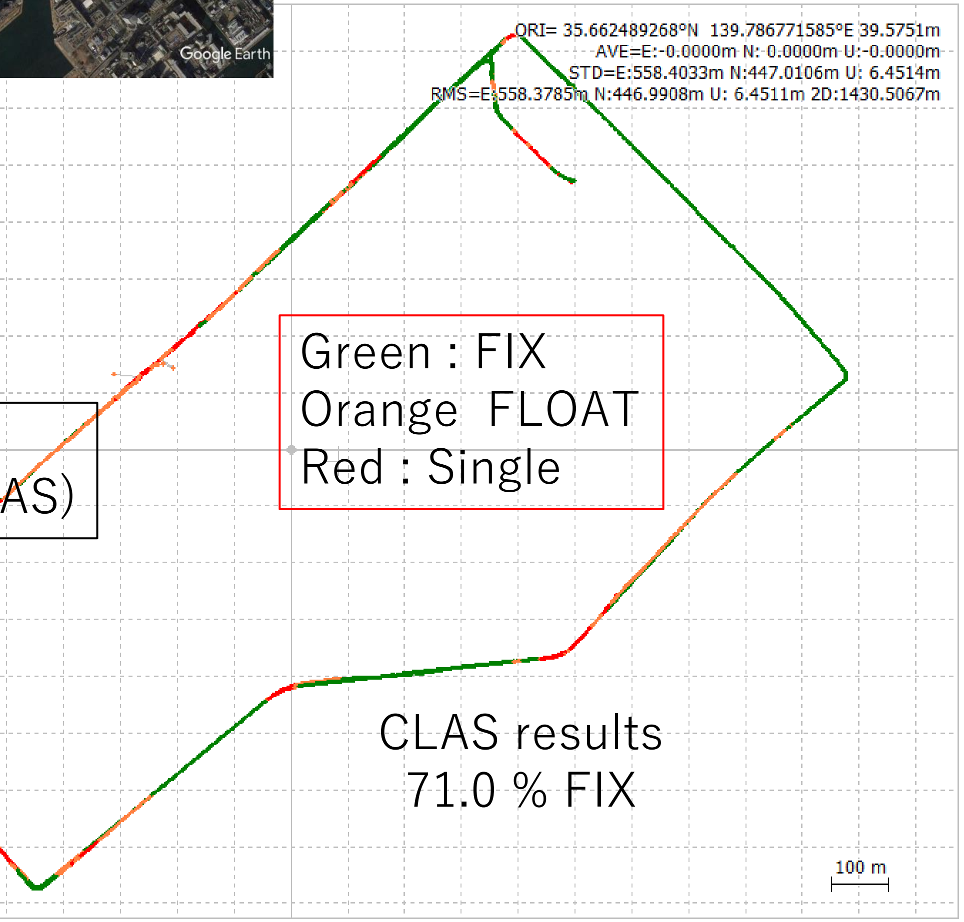


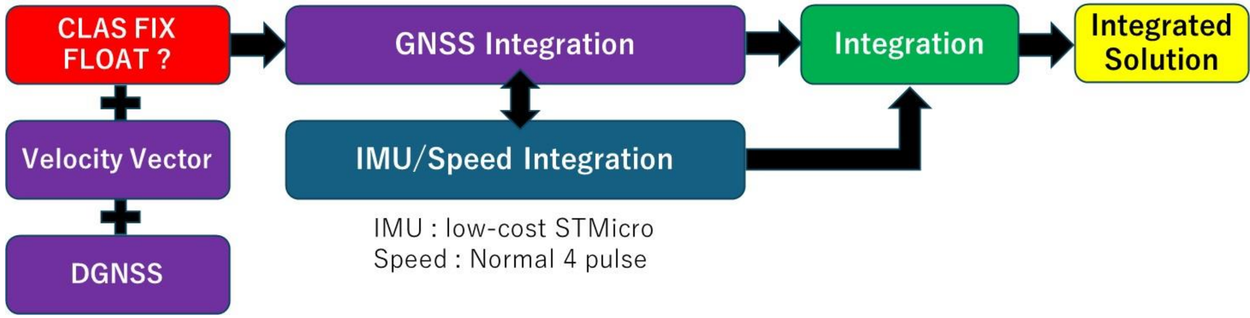
CLAS/IMU/Speed integration



Test course in
normal urban area

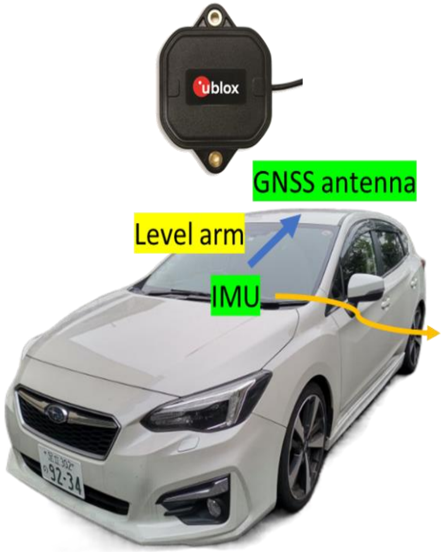
Core
AsteRx4(CLAS)

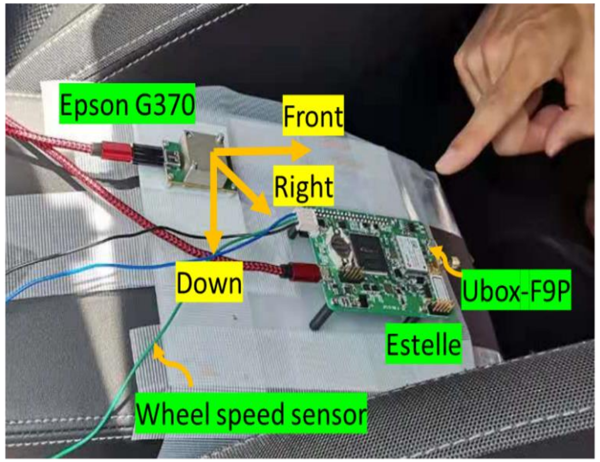




IMU : low-cost STMicro
Speed : Normal 4 pulse

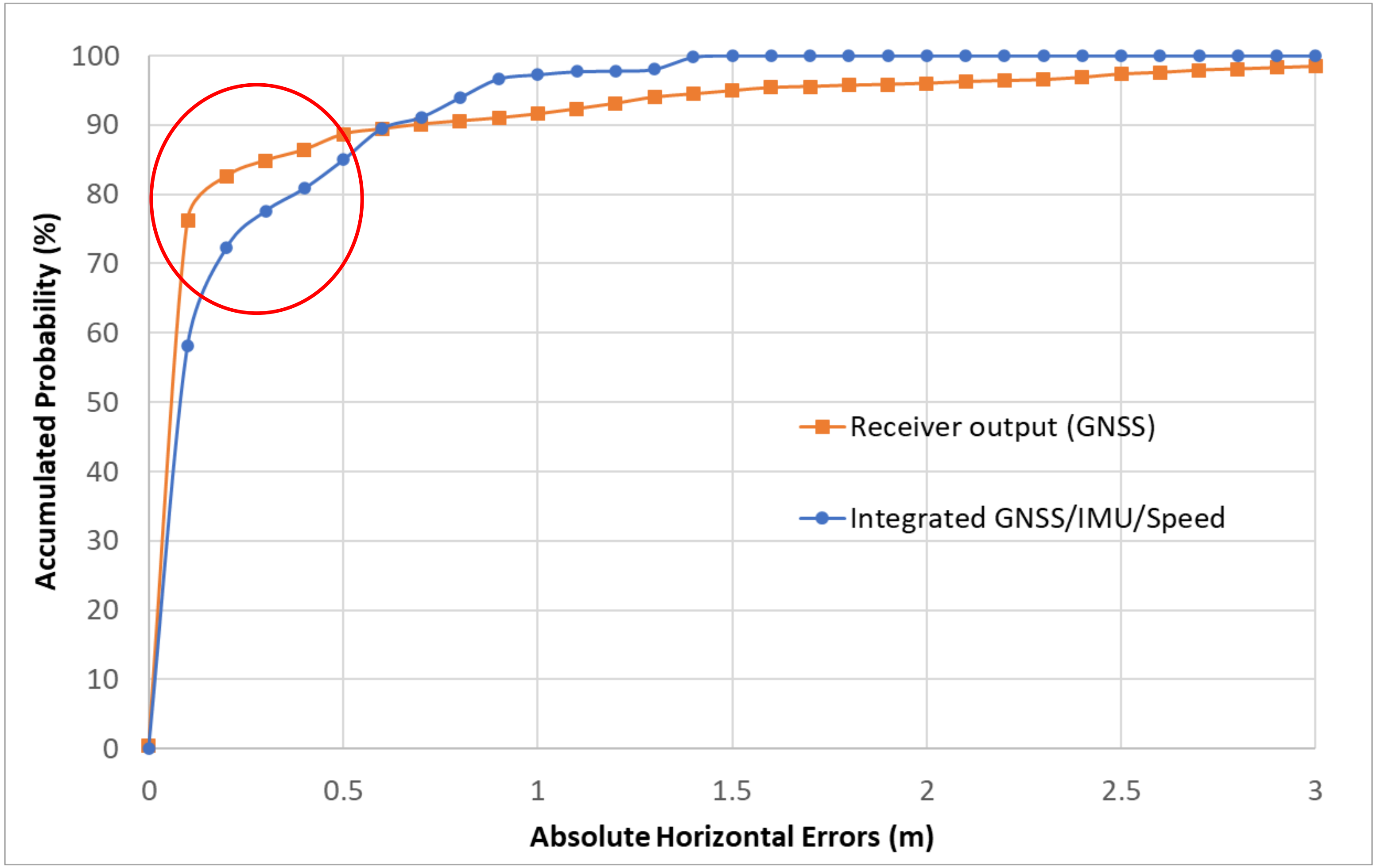
+





Horizontal Errors (Original vs. Integration)

GNSS LAB Tumsat



Absolute Horizontal Errors

Percentile	Original receiver	GNSS/IMU/ Speed
90 %	0.68 m	0.61 m
95 %	1.52 m	0.84 m
99 %	3.16 m	1.36 m
99.9 %	46.54 m	1.41 m
MAX	46.73 m	1.42 m

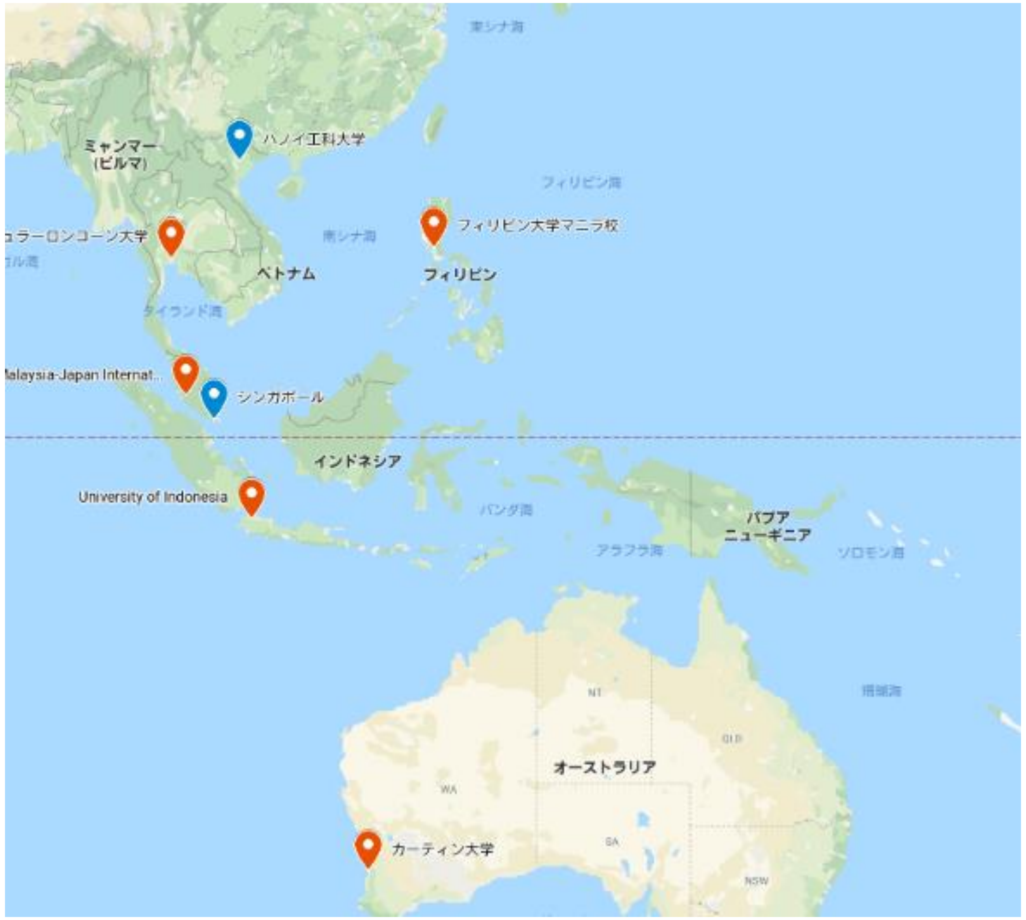
Interestingly, the integrated performance was worse than the original receiver (only GNSS) **within 50 cm** because **float solutions are not used for this integration**.

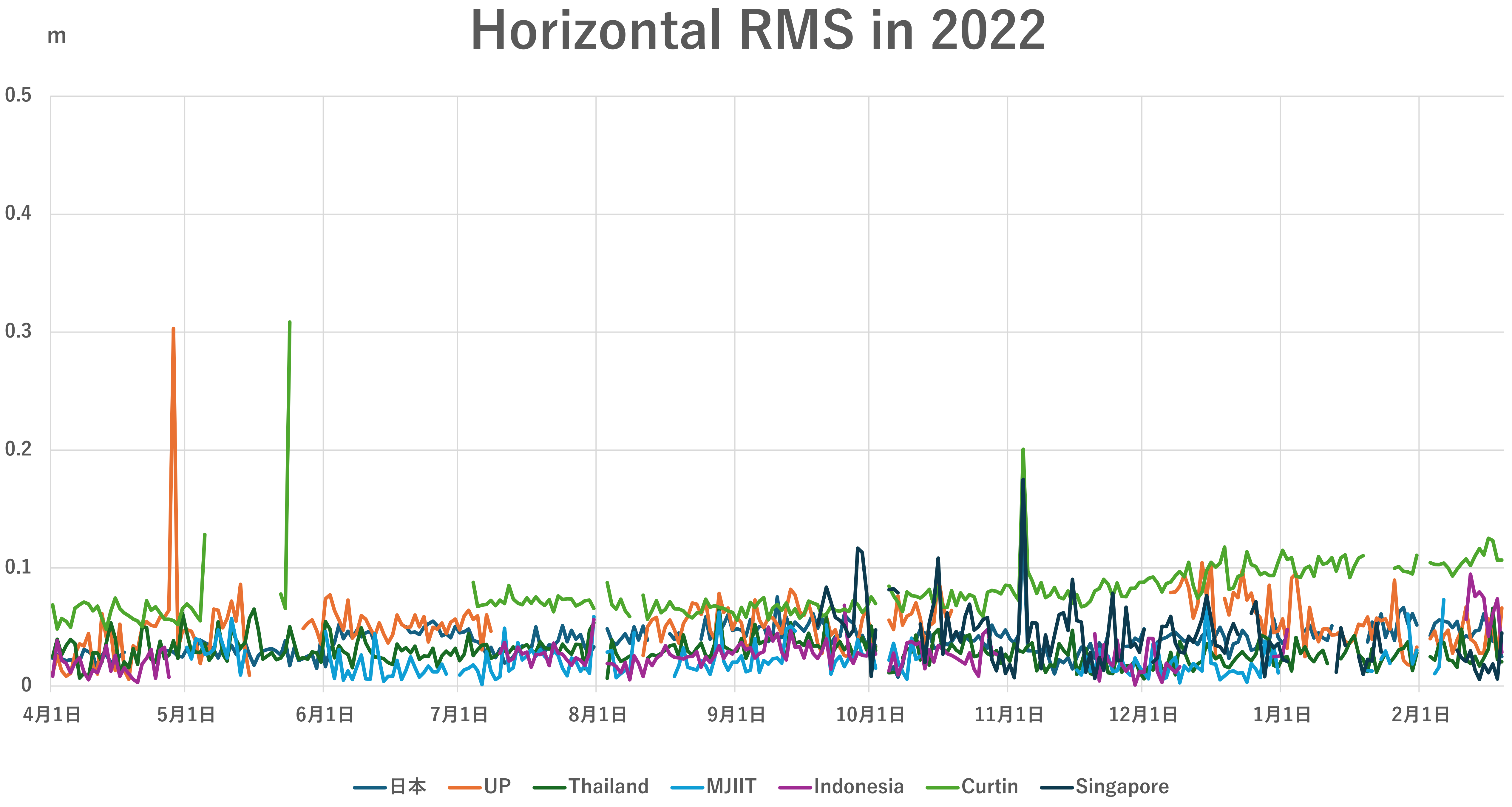
Long term evaluation of MADOCA PPP

NMEA
(PPP)

Locations (Time)

- TUMSAT JAPAN（August 2019）
- Chula Thailand（August 2019）
- UOP Philippine（August 2019）
- MJIIT Malaysia（Nov. 2019）
- Curtin Australia（Nov. 2019）
- UOI Indonesia（Dec. 2019）
- Singapore（Feb. 2021）
- Vietnam（March 2023）

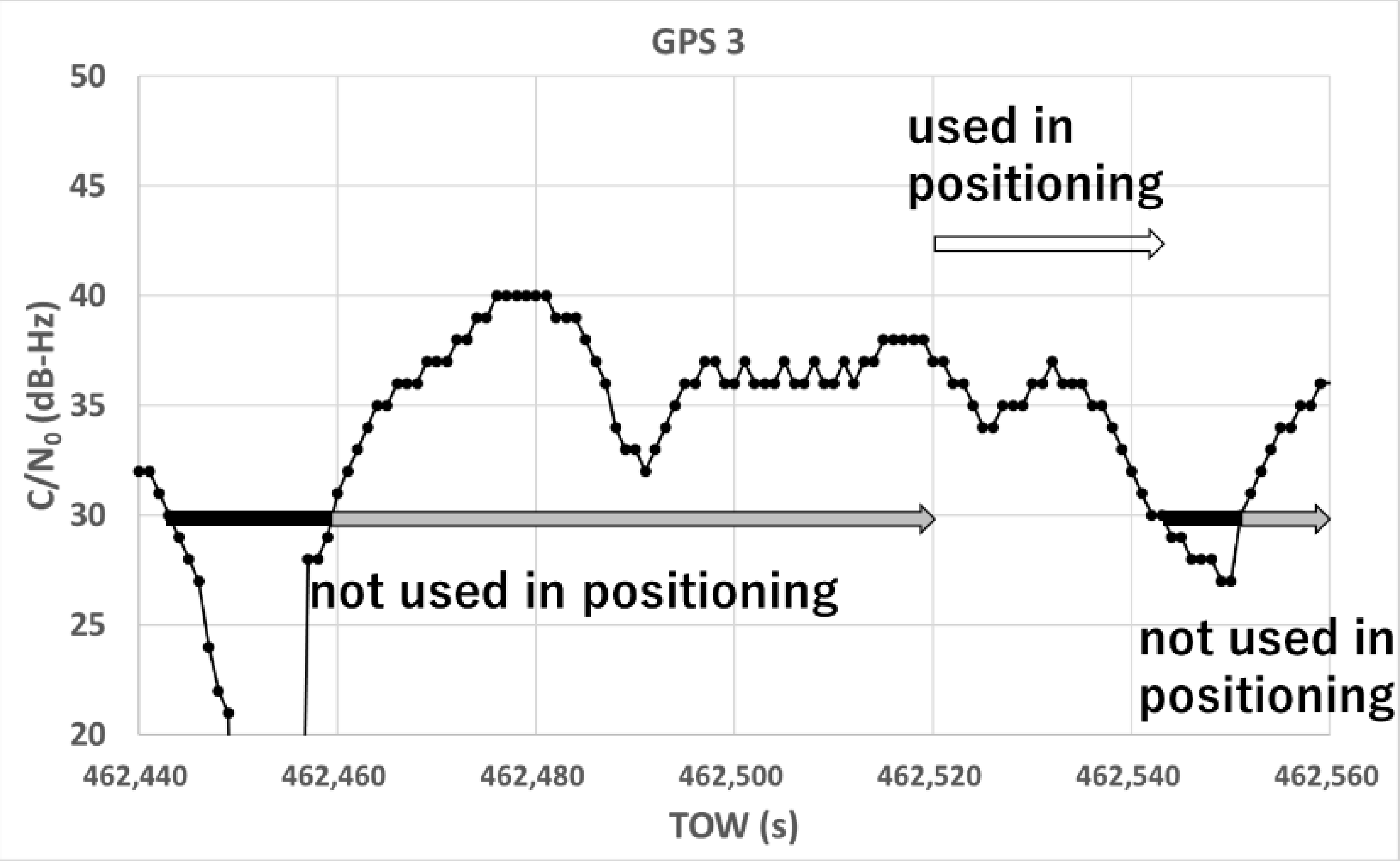




Horizontal RMS in 2022
m
0.5
0.4
0.3
0.2
0.1
0
4月1日
5月1日
6月1日
7月1日
8月1日
9月1日
10月1日
11月1日
12月1日
1月1日
2月1日
日本
UP
Thailand
MJIIT
Indonesia
Curtin
Singapore

New concept for detecting NLOS satellites

Temporal C/N_0 for GPS 03 depicted in the previous test



- When the value of the satellite C/N_0 is less than the threshold, the satellite is not used for positioning for a certain period.
- Two important parameters needed to be set for this method: the C/N_0 threshold and the period in which the satellite was not used for positioning.
- As an example, we set 30 dB-Hz and 1 min as the threshold and period, respectively. Even if the value of C/N_0 recovered over 30 dB-Hz after 462,460 s, the satellite was not used for positioning for at least 1 min.
- In reality, GPS 03 should not be used for positioning during all the time because the pseudo-range error was continuously large over 60 m.

Test configuration (car parking)

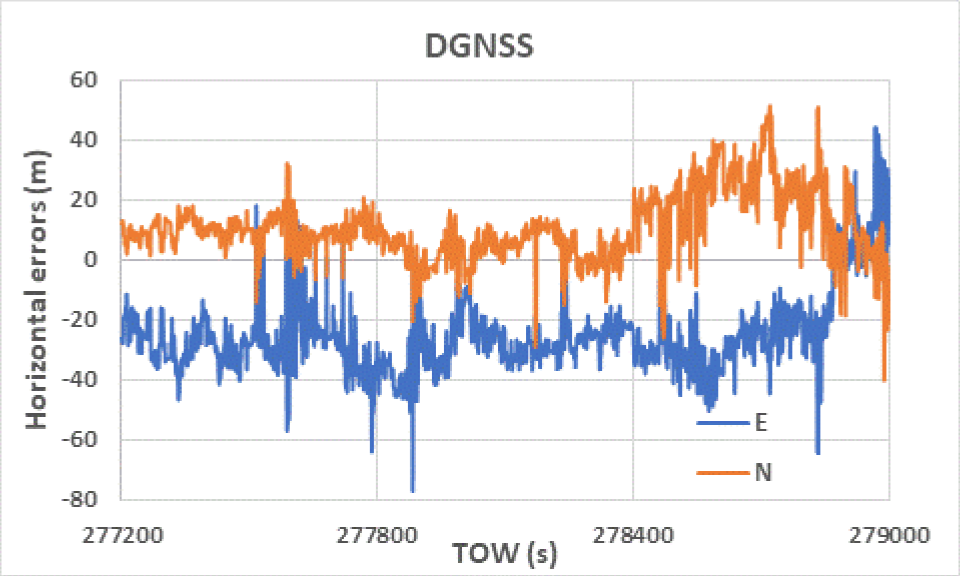
Sensor	Model Name
GNSS receiver	u-blox F9P (base/rover)
GNSS antenna (rover)	Standard patch antenna (ANN-MB-00-00)
GNSS antenna (base)	Trimble Zephyr 2 Geodetic

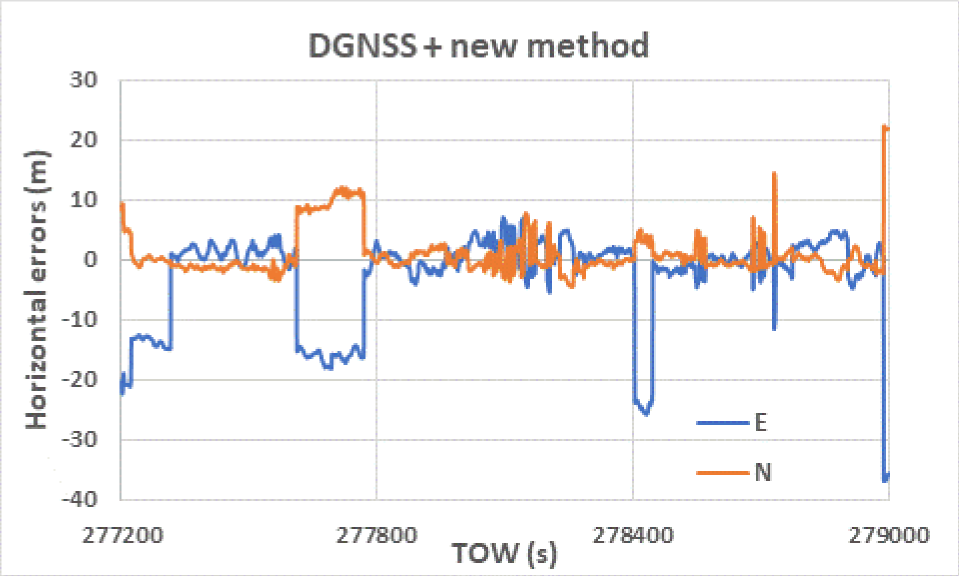
Item	Parameter
Mask angle	15 degrees
Maximum HDOP / Minimum C/N_0	10.0 / 30.0dB-Hz
Pseudo-range measurements	Tracked
Carrier phase measurements	Tracked
Carrier phase measurements (only RTK-GNSS)	Tracked and half-cycle resolved
Threshold for residual (least-squares method)	10.0 m

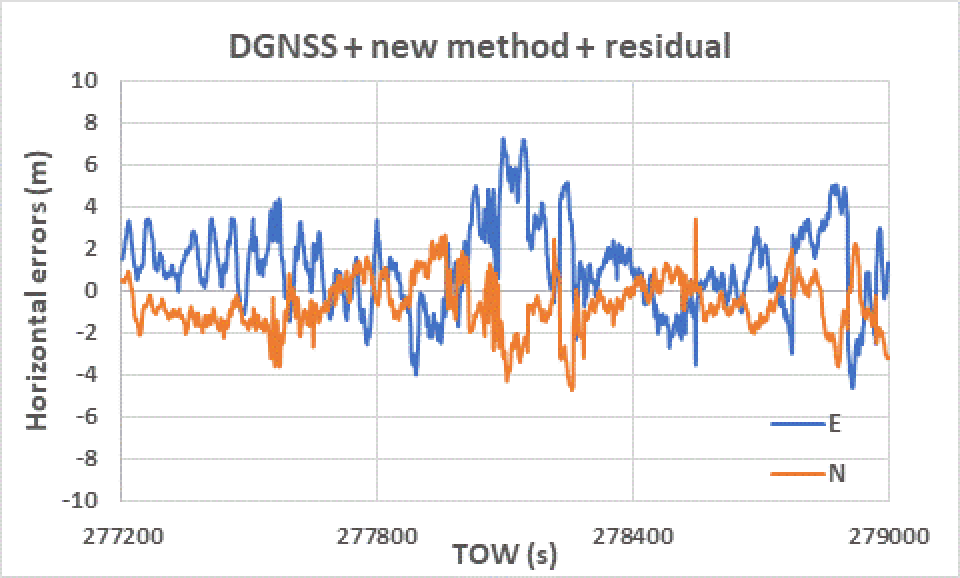
Detailed images around the antenna (1st location)

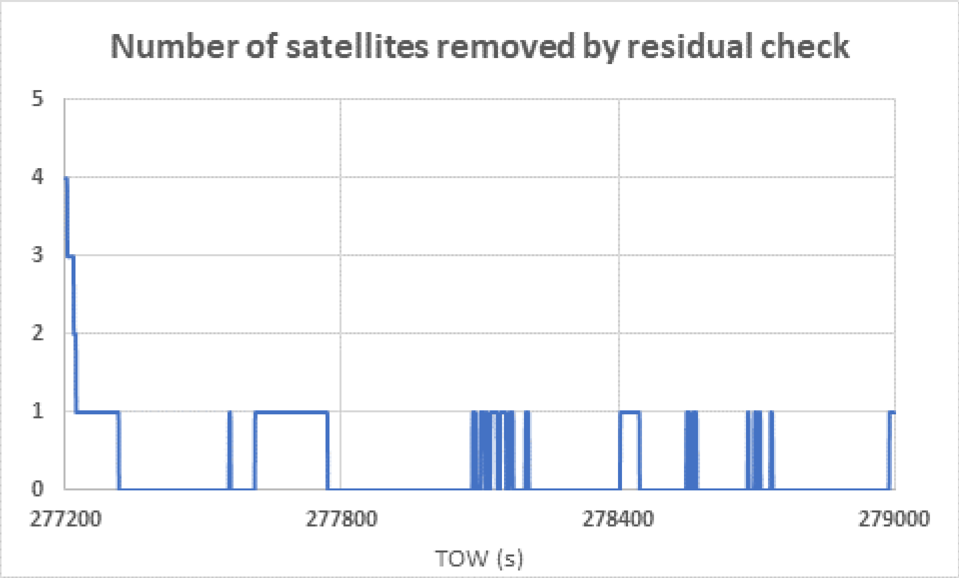
Detailed images around the antenna (2nd location)

Horizontal errors comparison (1st location)

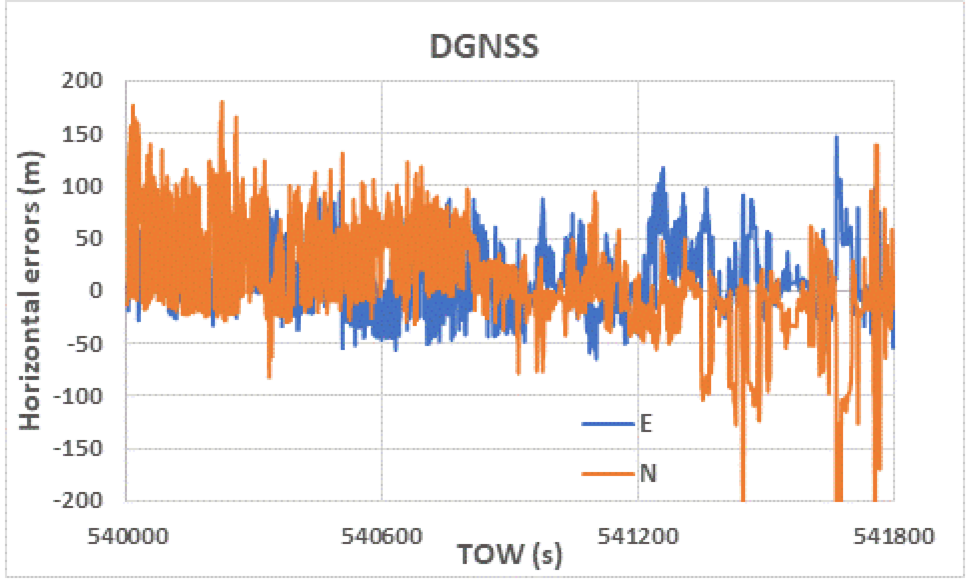


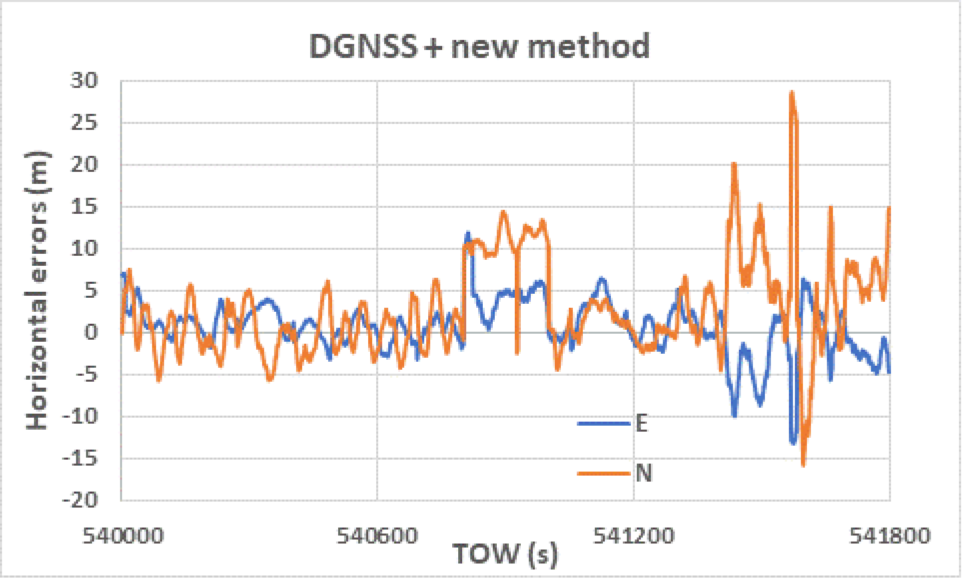


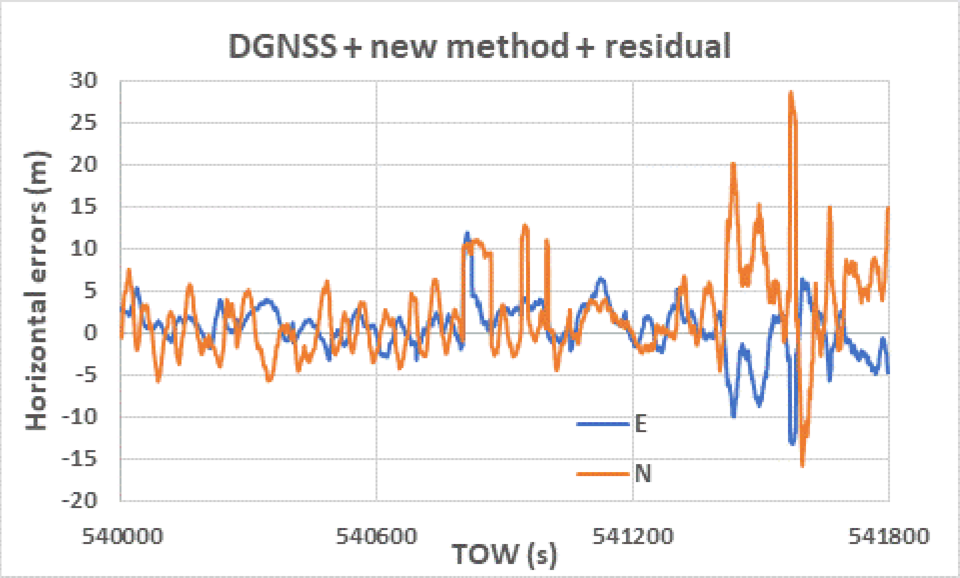


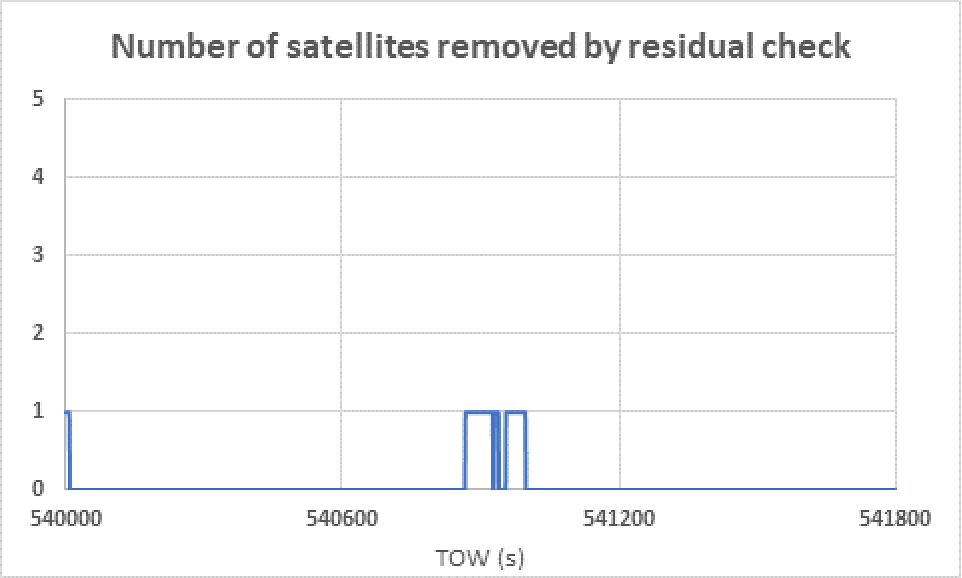


Horizontal errors comparison (2nd location)

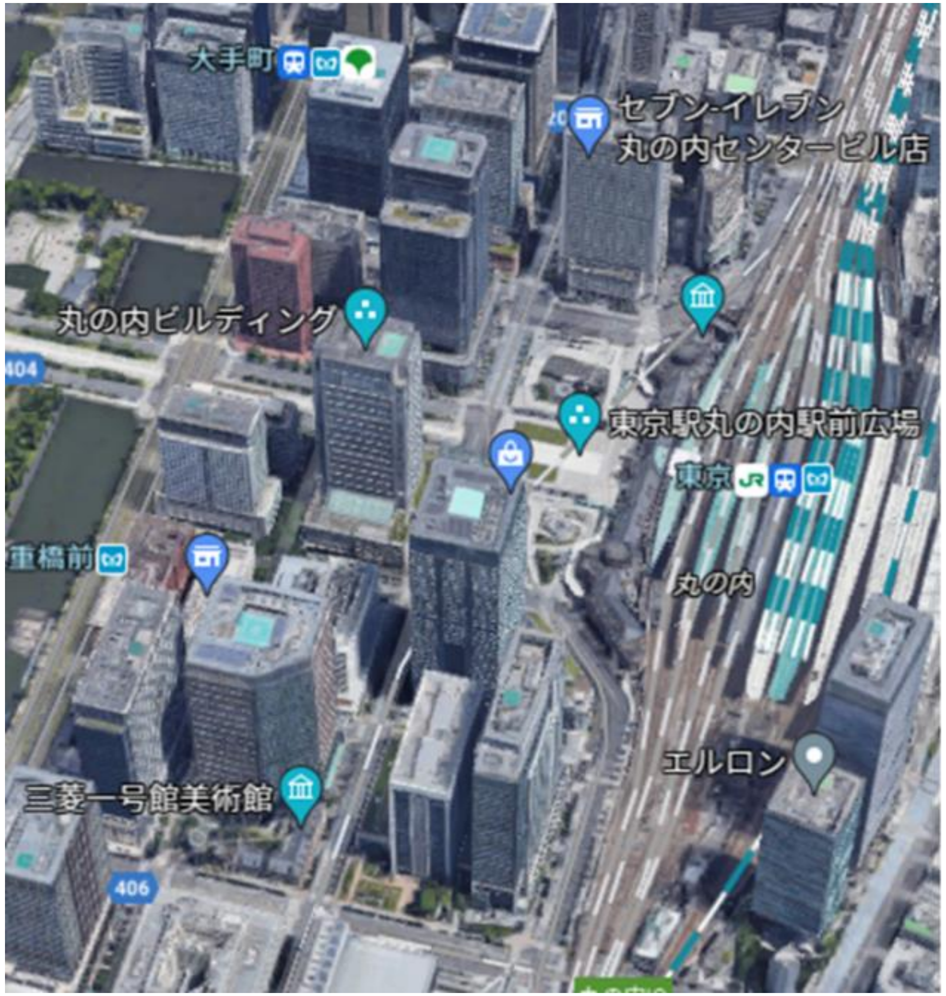


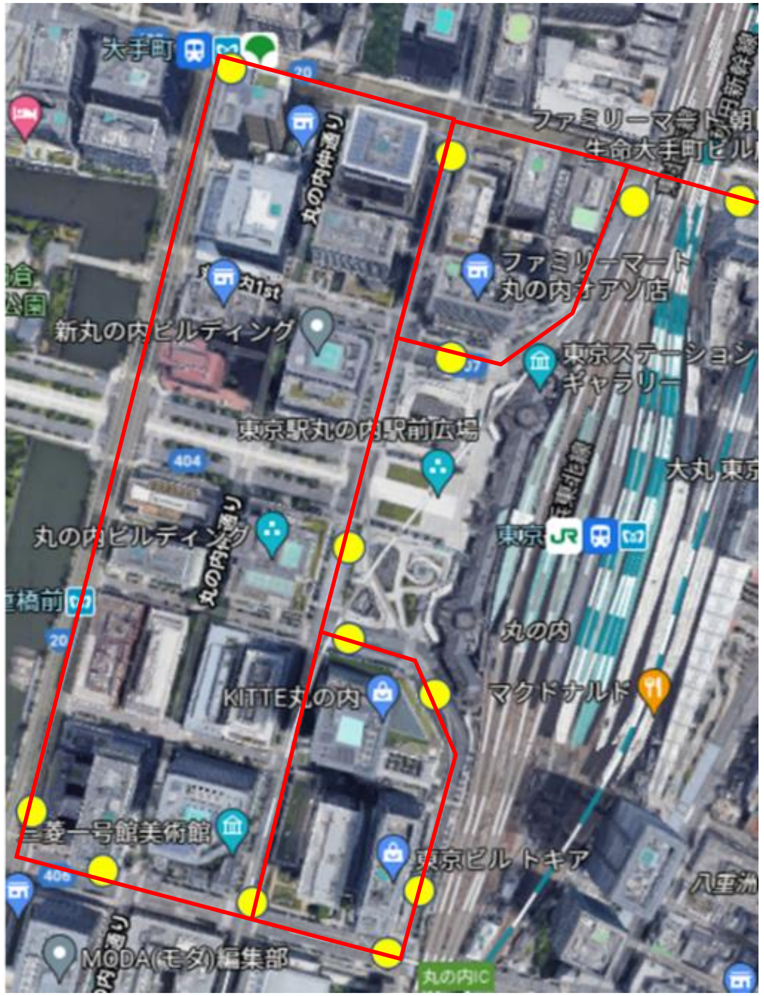






Test configuration (traffic signals)



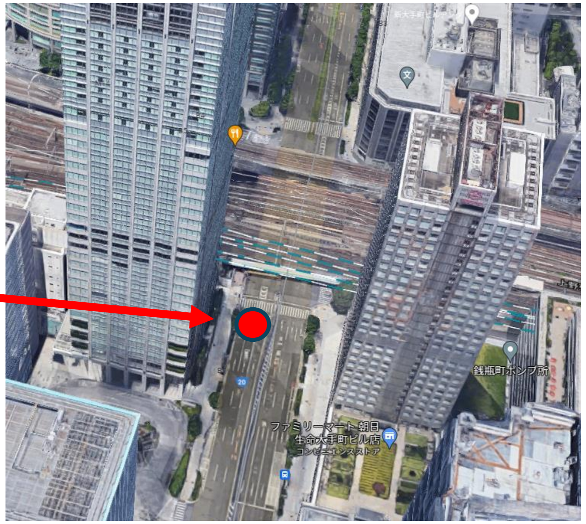


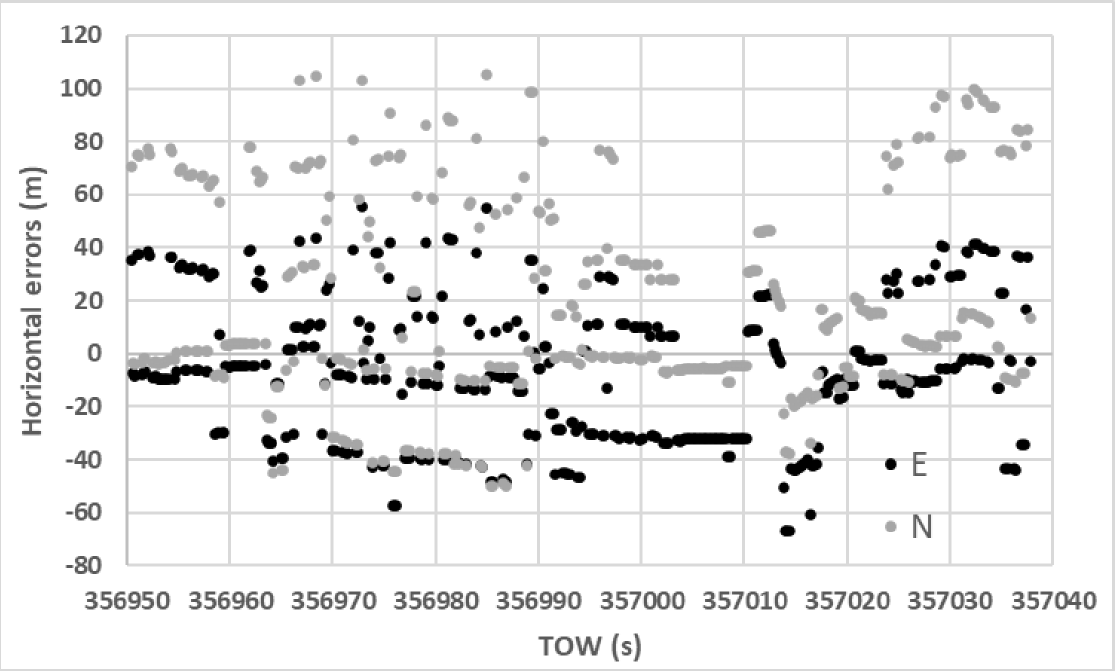
- Sensors and parameters are same as before.
- The route and 14 locations of traffic signals for this evaluation were shown in left figure.
- In fact, the car stooped in almost same locations 4 out of 18 times. Therefore, there were 14 locations are marked on the ground map.
- We have selected locations that have been stopped for more than 10 seconds.

Sep. 2021

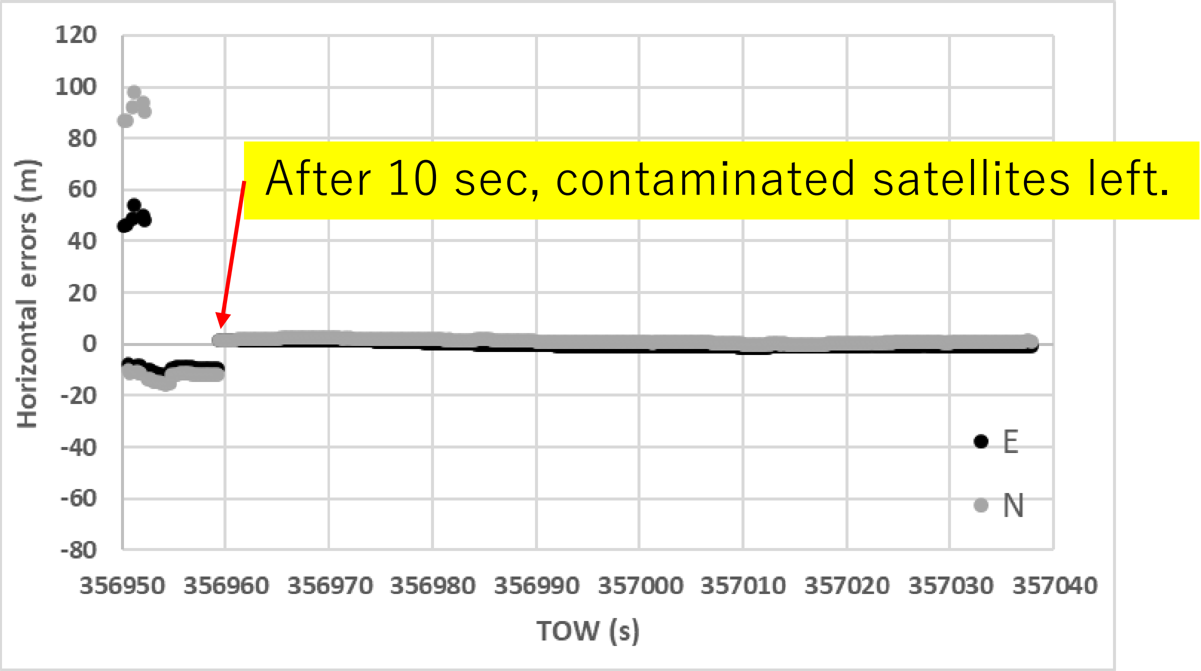
Horizontal errors comparison (1st traffic signal)

Approx. 90 sec stop





DGNSS horizontal errors



DGNSS horizontal errors using new method

Not only error mitigation but also we could see quick and correct detection of NLOS signals

Summary of RTK-GNSS

- Table summarizes the result of RTK-GNSS (modified RTKLIB) in all locations. **S** means we got correct solutions with RTK-GNSS. **F** means we didn't get correct solutions with RTK-GNSS. We were able to get correct solutions with RTK-GNSS in **6 more locations** using the new satellite selection method. The **number of wrong fixes** of RTK-GNSS without the new satellite selection method was **high**, and the number of wrong fixes of RTK-GNSS with the new satellite selection method was **quite low**.

RTK-GNSS with/without new satellite selection method **(S : Success,　F : Failure)**

Locations	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Normal	F	F	F	F	F	S	S	S	S	F	F	F	F	F	S	S	F	F
New Method	S	S	F	F	F	S	S	S	S	S	S	F	S	F	S	S	S	F

Flowchart of methodology (Modified RTKLIB)

GNSS Raw Date from RTKLIB

↓

Initial Parameters

↓

Initial Satellite Selection

→

Float Solution and Velocity Estimation ↔ Pseudo-range residual check

↓

Subsets of GNSS Satellites

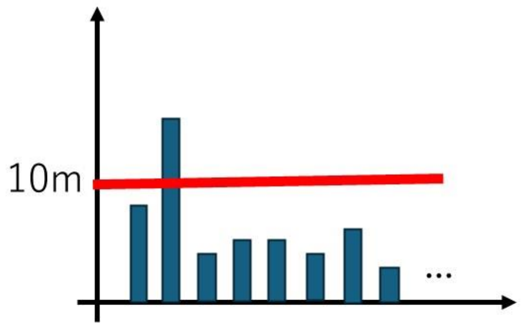
↓

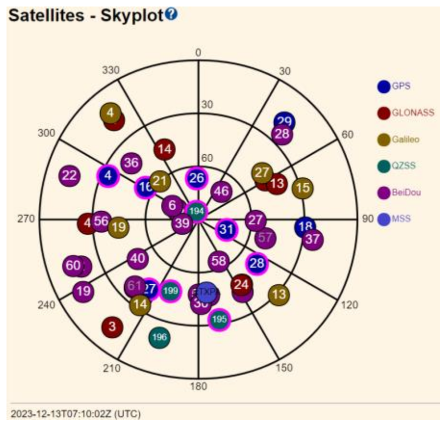
RTK-GNSS with Velocity Vector

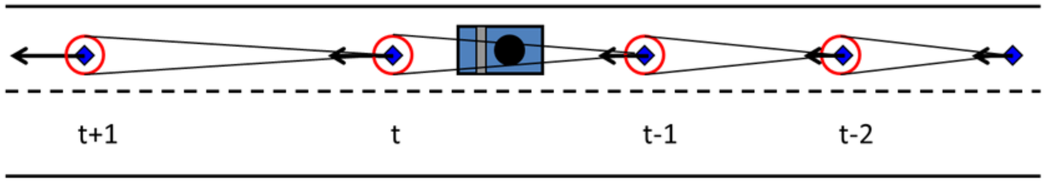
↓

Position Solution to RTKLIB

Mask angle : 10 degrees
Minimum C/N_0 : 35 dB-Hz





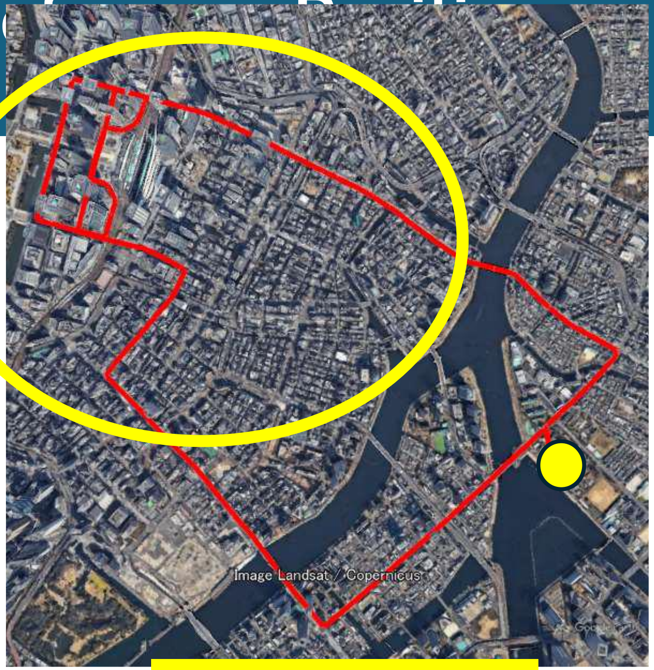


Expected Position (t) = Previous Fix Position(t-1) + (Velocity(t)+Velocity(t-1))/2

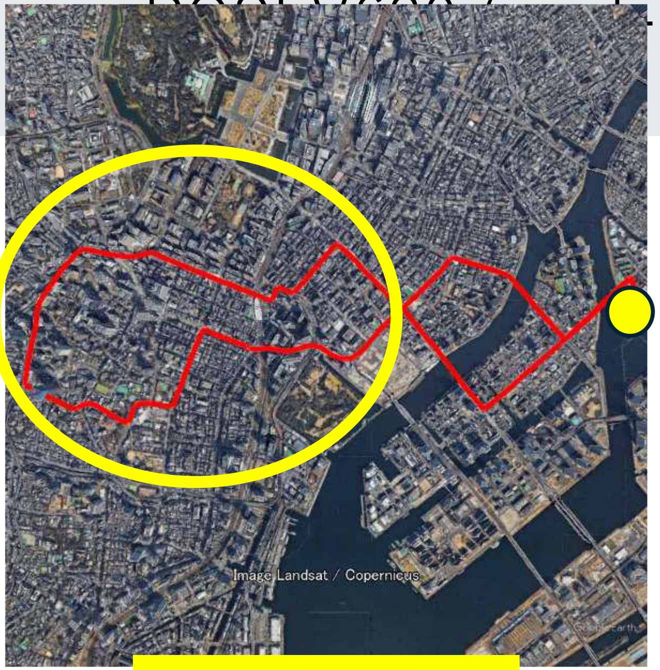
Interval = 1.0 sec

Data collection

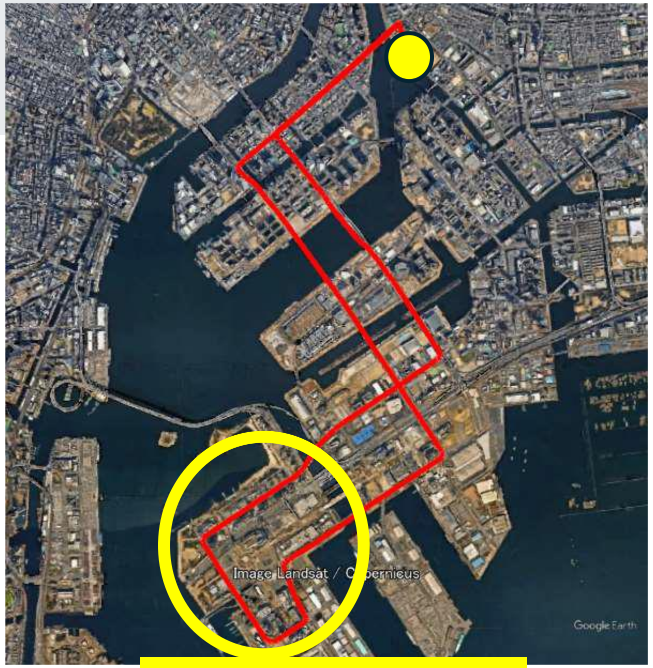
Sensor	Model name
GNSS Receiver (base and rover)	u-blox F9P
GNSS Antenna (rover)	Trimble AT1695
GNSS Antenna (base)	Trimble Zephyr 2 Geodetic



Test1 3,360 s



Test2 3,088 s



Test3 2,852 s

Comparison with commercial receiver

Test number	Modified RTKLIB		Commercial receiver (u-box F9P)	
	Fix rate	Horizontal 2DRMS	Fix rate	Horizontal 2DRMS
First test course	66.8 %	0.53 m	52.2 %	0.32 m
Second test course	58.0 %	1.34 m	47.9 %	0.82 m
Third test course	67.8 %	0.20 m	74.2 %	0.54 m

Comparisons with RTKLIB/rtklibexplorer

- For the ambiguity resolution method, the **instantaneous mode** was used because the instantaneous mode is the best of the three modes using **RTKLIB** in urban areas.
- For the ambiguity resolution method, the **Fix and Hold mode** was used because the Fix and Hold mode is the best of the three modes using **rtklibexplorer** in urban areas.
- The following table summarizes the setting values of the parameters for RTK-GNSS. Each parameter to produce best performance was searched by changing these values. In fact, **Min Lock to Fix Amb** was also used here.

Parameters	Setting values
Mask angle	10, 15, 20, 25, 30, 35
Minimum C/N_0 (dB-Hz)	30, 32, 34, 36, 38, 40, 42, 44
Code/Carrier ratio	100, 200, 300

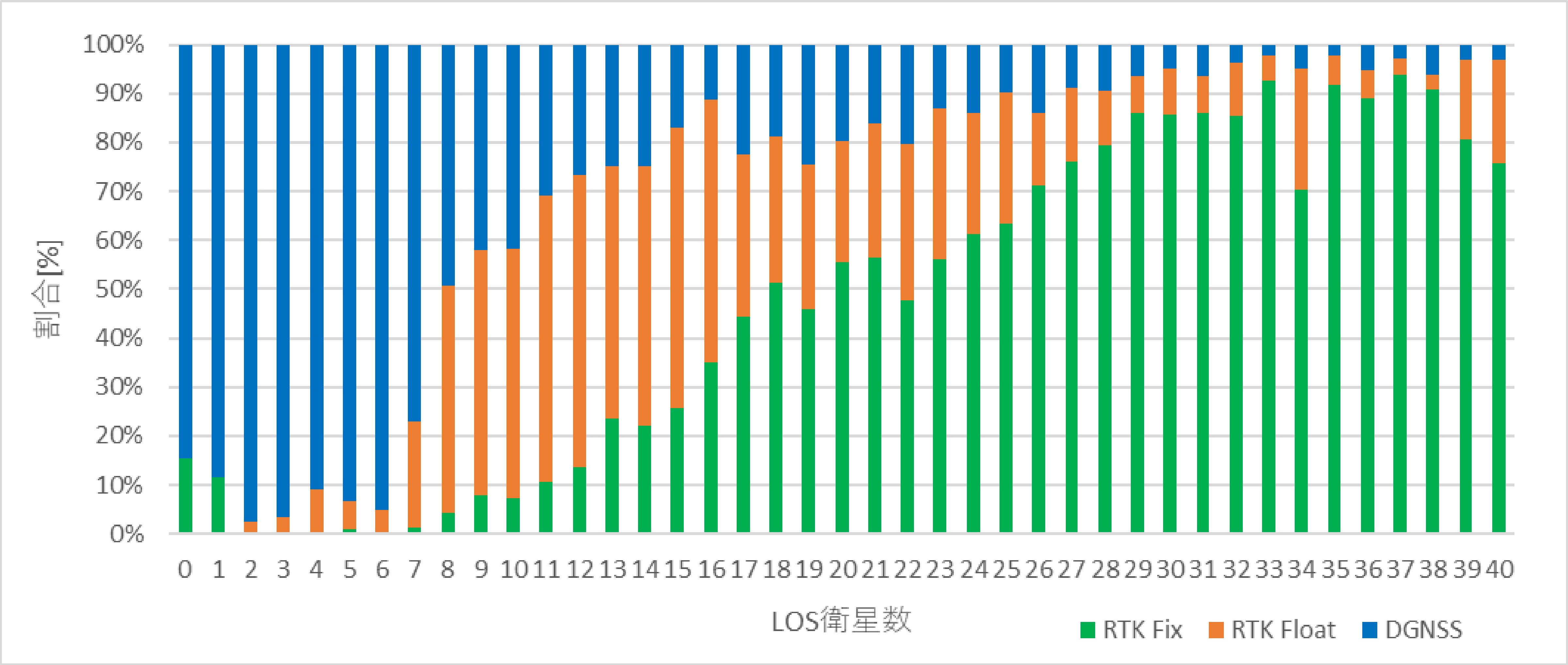
Comparison with RTKLIB

Test number	Modified RTKLIB		RTKLIB	
	Fix rate	Horizontal 2DRMS	Fix rate	Horizontal 2DRMS
First test course	66.8 %	0.53 m	41.1 %	7.69 m
Second test course	58.0 %	1.34 m	34.3 %	7.36 m
Third test course	67.8 %	0.20 m	54.3 %	11.23 m

Comparison with rtklibexplorer

Test number	Modified RTKLIB		rtklibexplorer	
	Fix rate	Horizontal 2DRMS	Fix rate	Horizontal 2DRMS
First test course	66.8 %	0.53 m	64.3 %	1.24 m
Second test course	58.0 %	1.34 m	60.8 %	2.35 m
Third test course	67.8 %	0.20 m	72.5 %	0.39 m

Relationship between Number of LOS and RTK fix rate



Relationship between Number of LOS and RTK FIX rate (2021)
Location : Mostly downtown in Tokyo

1. Number of satellites with continuous LOS
2. PDOP of the above constellation
3. Sky factor
4. Number of satellite with NLOS
5. Number of DD for each constellation

DOP, N of SATs etc. simulated by 3D map and ephemeris (Explanatory var.)

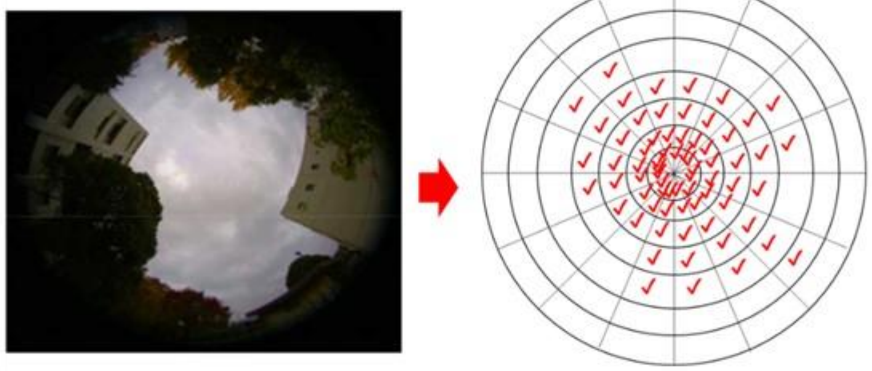
Actual solution status (Answer)

Learning

Machine Learning

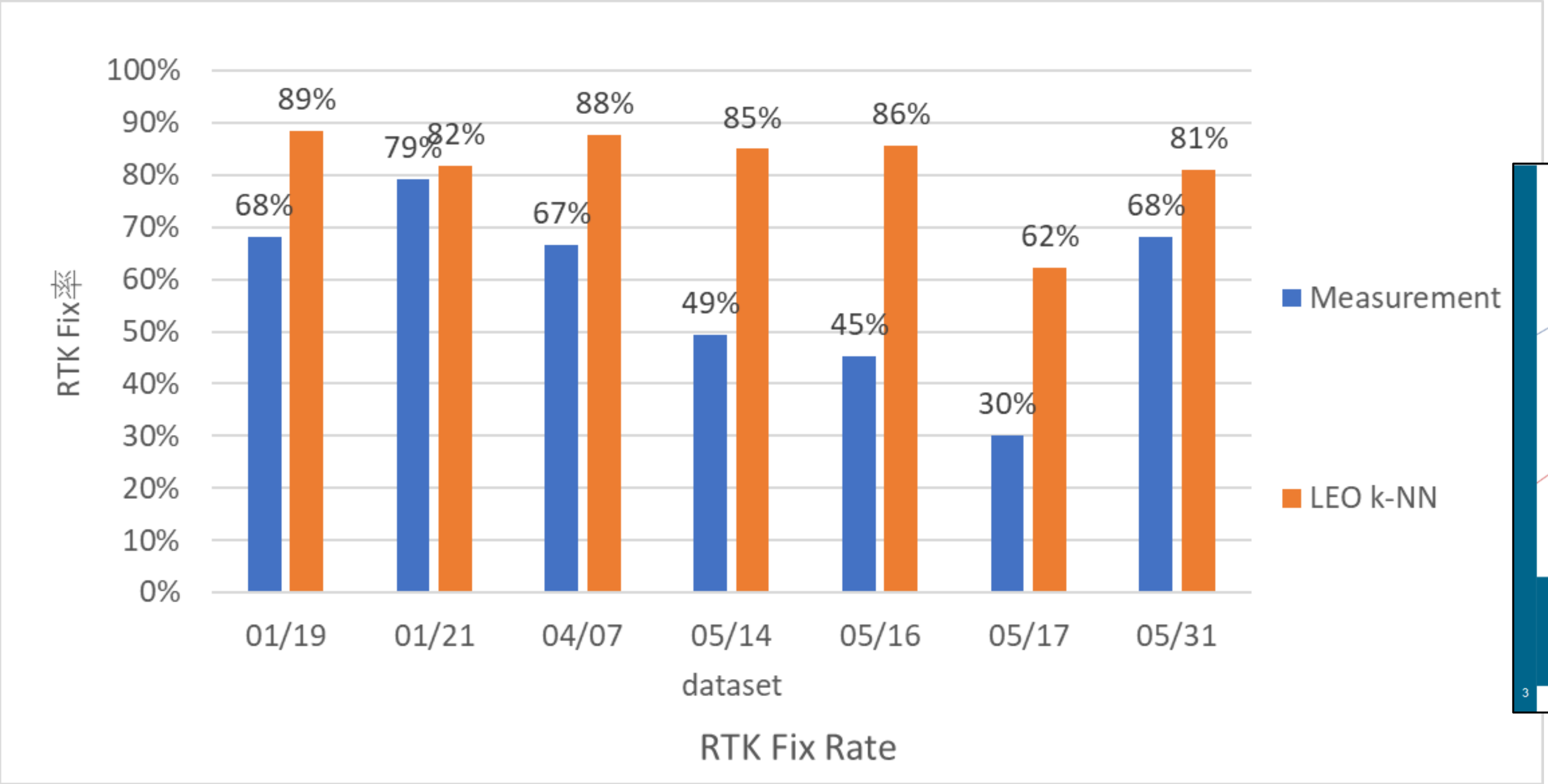
DOP, N of SATs etc. simulated by 3D map and ephemeris (Explanatory var.)

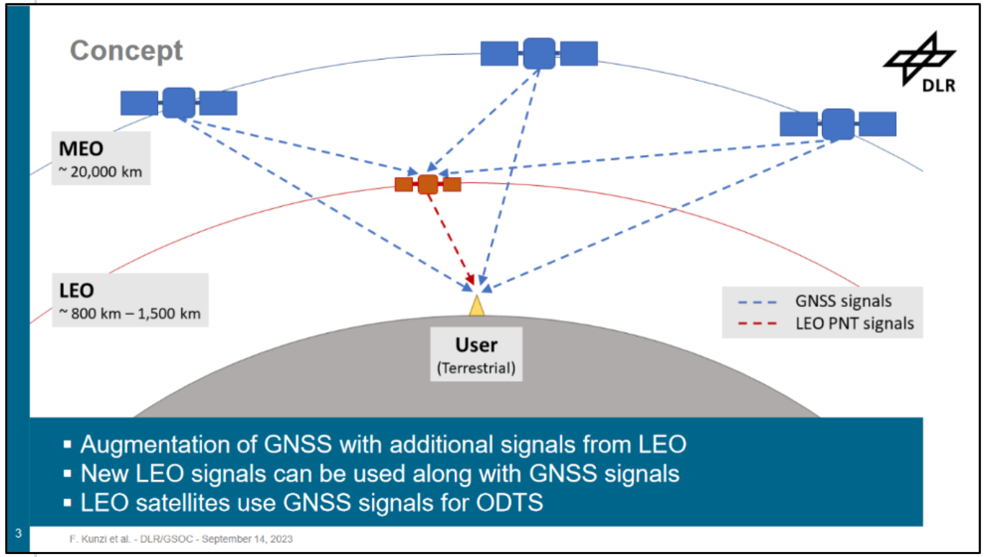
Solution status prediction (RTK FIX or NOT)



天空率の計算イメージ
(実際は1度グリッドで計算)

Height[m]	RTK Fix Rate		
	K-NN	Logistic Regression	DNN
0 (Measured)	68.2		
0	63.4%	59.1%	61.5%
30	86.7%	84.7%	85.4%
50	89.5%	88.3%	89.4%
100	98.9%	99.4%	99.8%





Thank you very much for your attention.