Modified RTKLIB for Kinematic Urban Condition

GNSS summer school 2025 (IPNTJ) , 9/4/2025 at TUMSAT

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Tokyo University of Marine Science and Technology

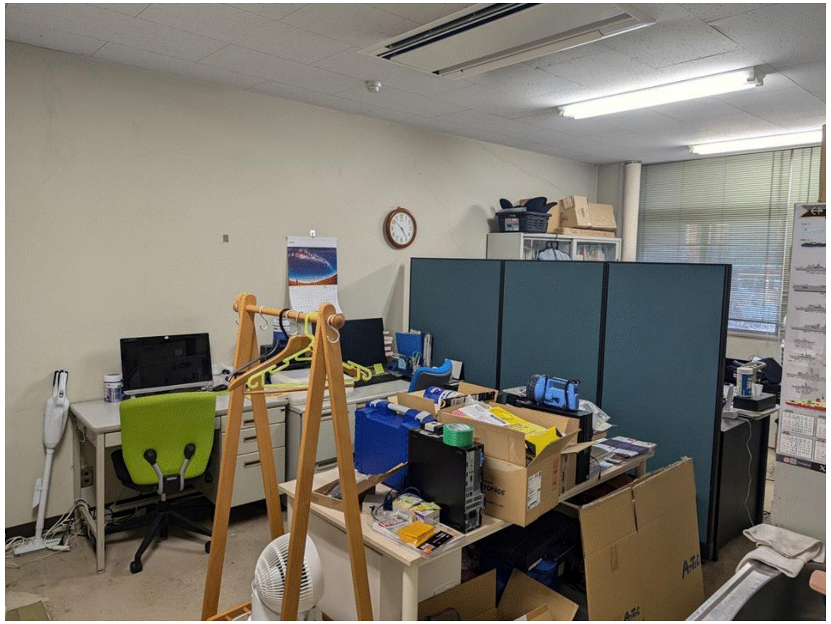
University and Laboratory

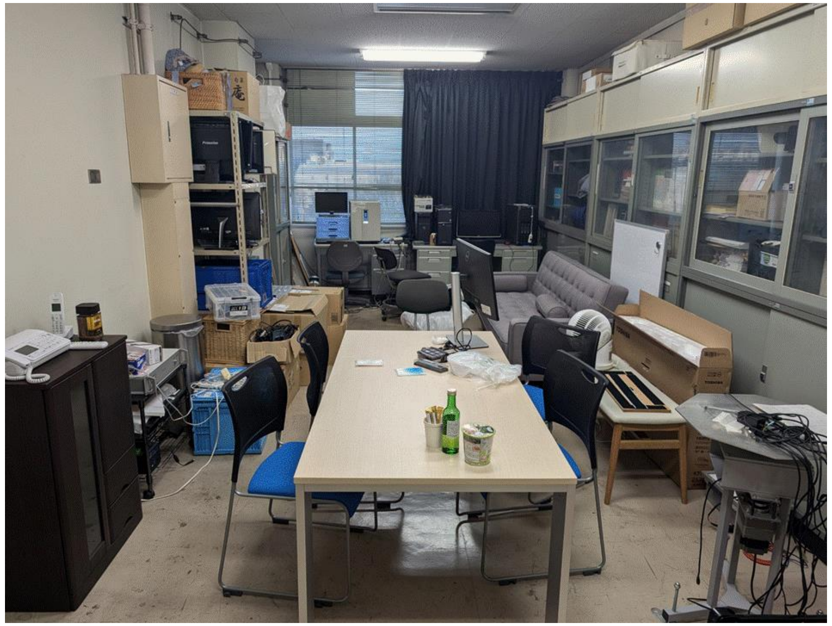
- **T**okyo **U**niversity of **M**arine **S**cience **a**nd **T**echnology
- Marine Technology and Marine Science
- Information and communication engineering laboratory (GPS/GNSS lab.)
- Staff 1 (2), Posdoc 1, Docter 3, Master 2, Undergraduates 7



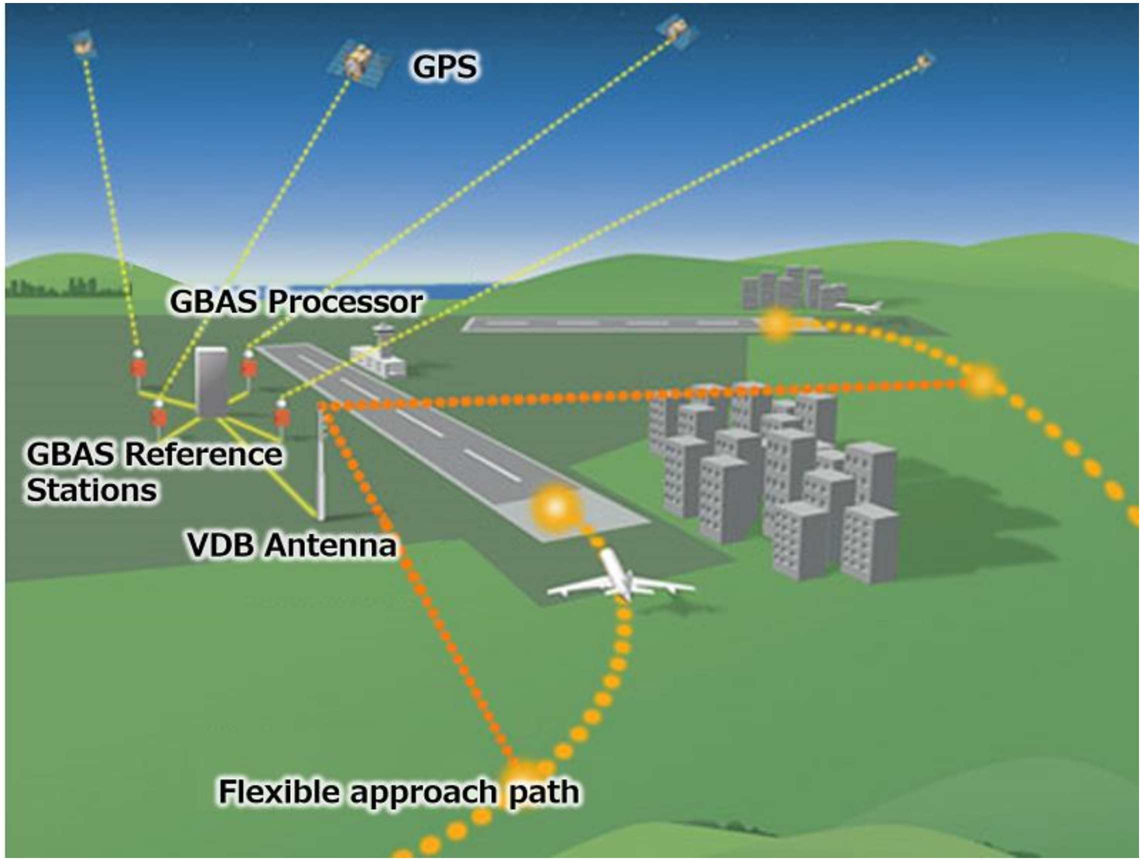
Laboratory

Every university has international students. Especially at the graduate level, there are many opportunities. In this laboratory, we also host many visiting students from overseas for short stays of one to two months (in 2024, from Germany and the United States; this year, from Taiwan and China).





The reason I became involved in GPS research



- Undergraduate studies: Electrical Engineering
- Master's studies: Simulation for space electric propulsion system
- Employment: Interested in aircraft landing systems using GPS (featured in newspaper at the time), joined NEC.
- Desired to learn the fundamentals of GPS itself. and became an assistant professor at TUMSAT. Ph.D. from the University of Tokyo.
- 4+23 years involved in GPS/GNSS. Spent 1.5 years at Stanford during this period.

Ground-based Augmentation System
→Precise Approach and Landing of Aircraft (Air Traffic Control))

Lab's theme

- We have been working on various topics related to GPS/GNSS for the past 20 years
- Will continue to work on issues related to position estimation and Navigation
- We are looking forward to more challenging themes and your simple thoughts and ideas for the next 20-30 year.
- We have many opportunities to collaborate with other universities and laboratories.

Background

- Solving **social issues using GNSS** in general → Students and I have grown and discovered new things as we work on this project
- Methods to determine outdoor locations with high accuracy have become **commoditized**.
- **Reliability** of estimated position is important.
- **People who know how GNSS works are still in demand**. If it's a black box, it's impossible to track down the cause when something goes wrong.
- Conduct research not only on technical matters, but also on **applications** more broadly
- A laboratory that can respond to your interests.

Concrete topics

- Research on Precise Estimation of Ship/Dynamics
- Research on the integration of Lidar/UWB and GNSS
- Research on utilization of correction data from QZSS
- Software defined Radio in GNSS + more
- Utilization of location information for traffic accident prevention
- Utilization of LEO (low earth orbit) satellites
- Precise position monitoring in various locations
- Simulation of GNSS in general

Some applications using RTK.

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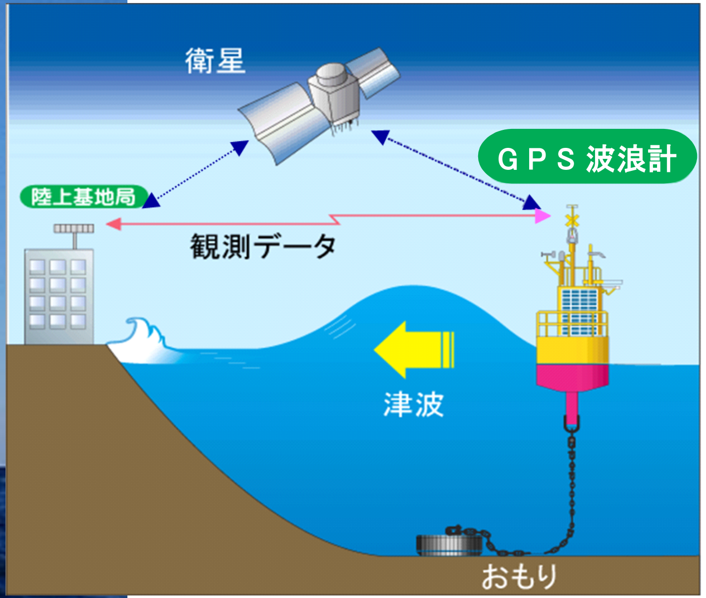
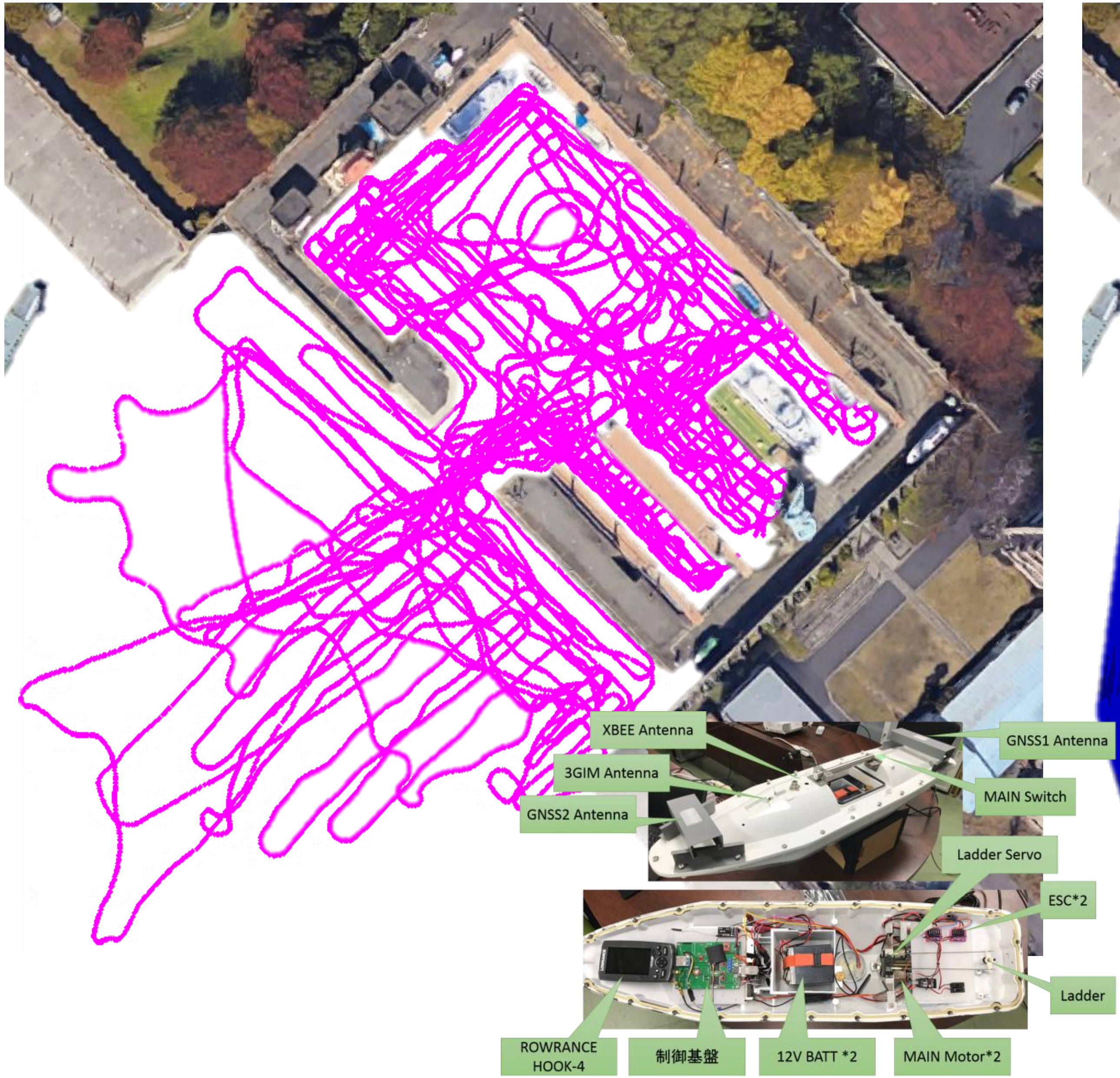
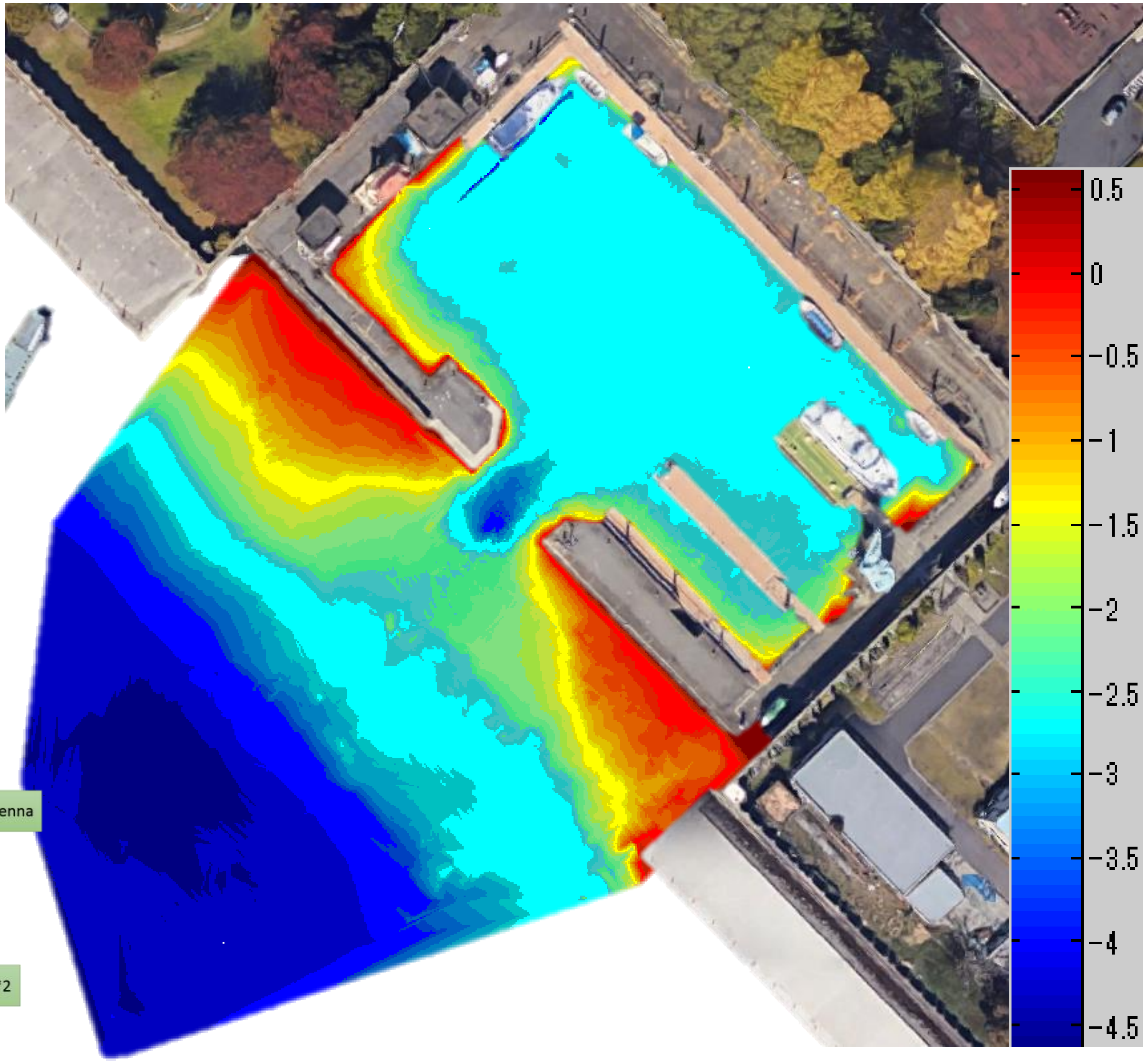
https://www.mlit.go.jp/kowan/nowphas/

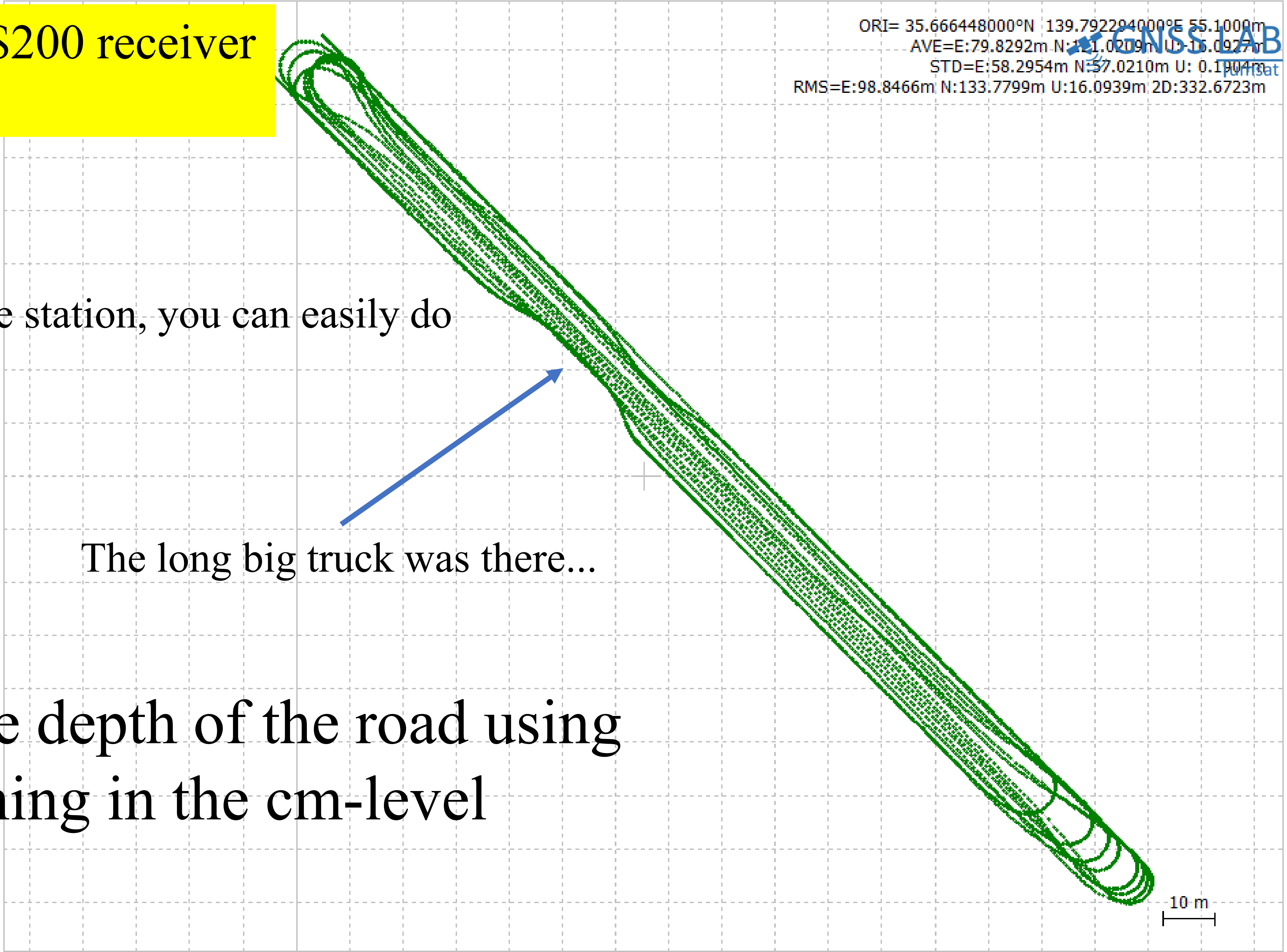


Trace Chart / Bathymetric Chart





RTK results from $200 receiver (10Hz, 15 min.)



Once you set up base station, you can easily do similar test.

Surveying the depth of the road using RTK positioning in the cm-level

This is the areal elevation data surveyed by RTK on Etchujima-street next to the university

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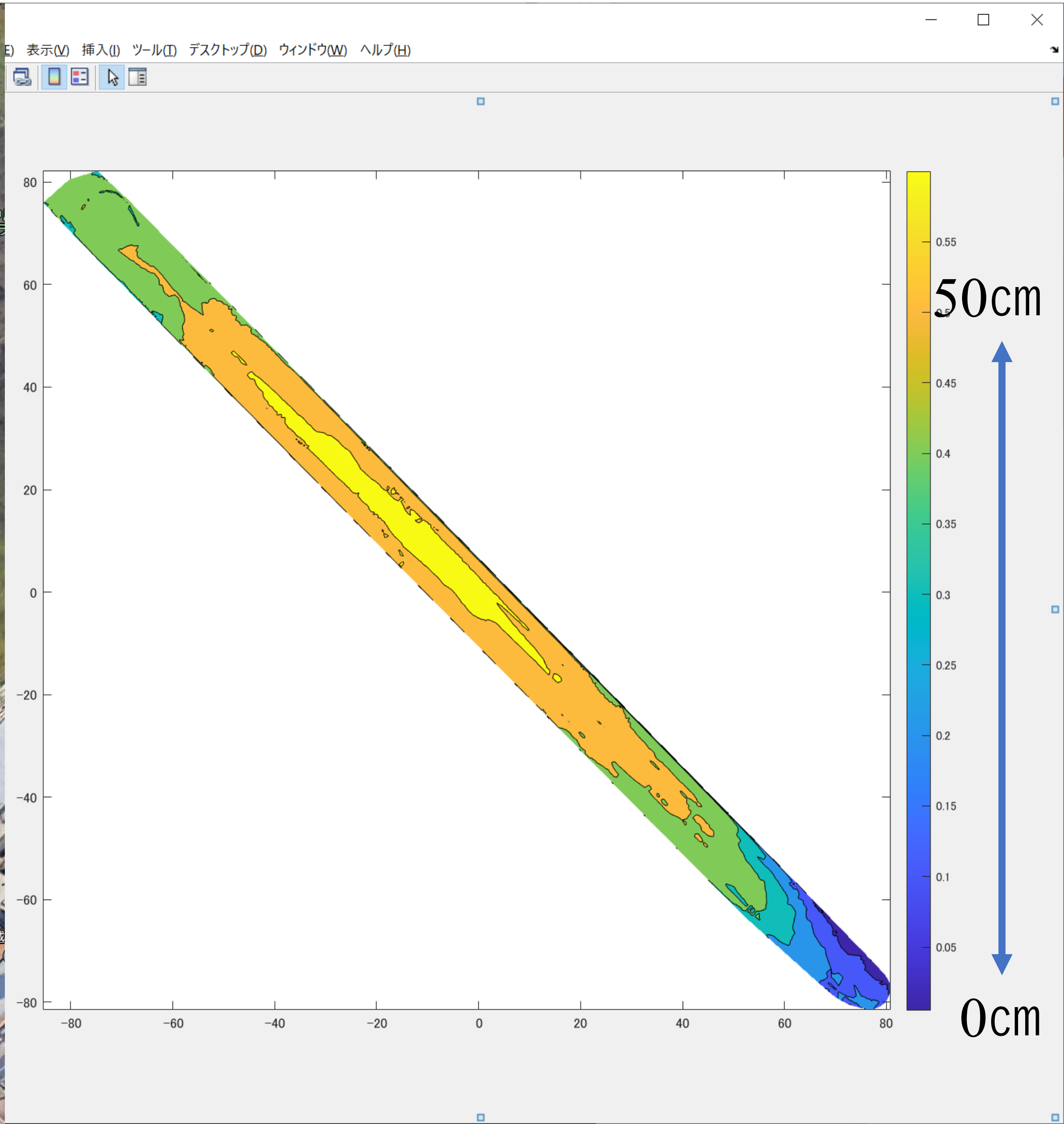

High-precision 3D map generation by GNSS/IMU/velocity sensor + Lidar

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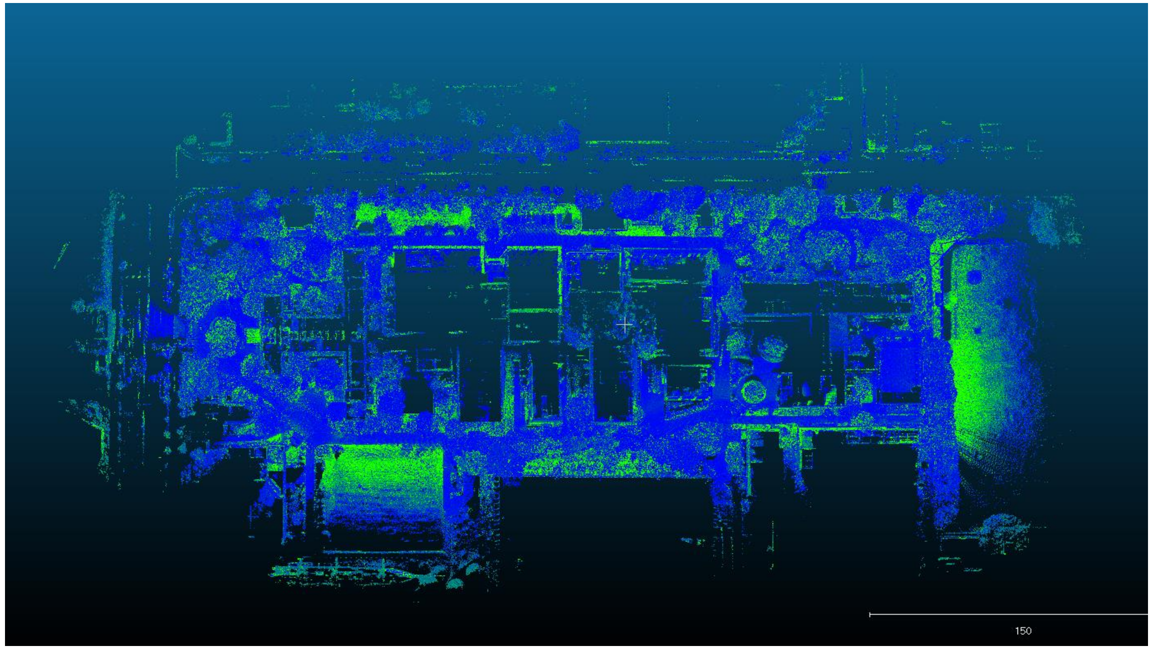
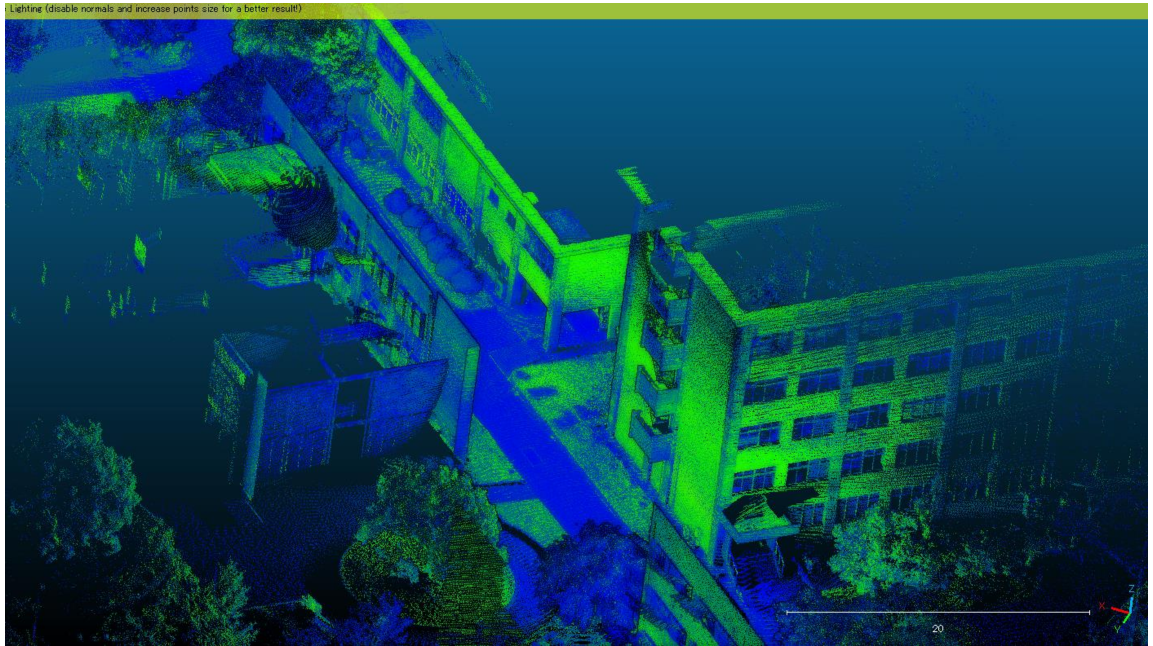


Campus



Nearby building

Precision map generation using drones

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This 2D map generated by students
Horizontal accuracy is below 10 cm level

Long-term evaluation of cm-level correction data by QZSS

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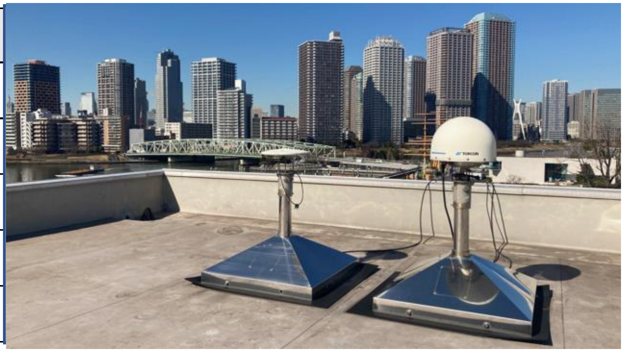
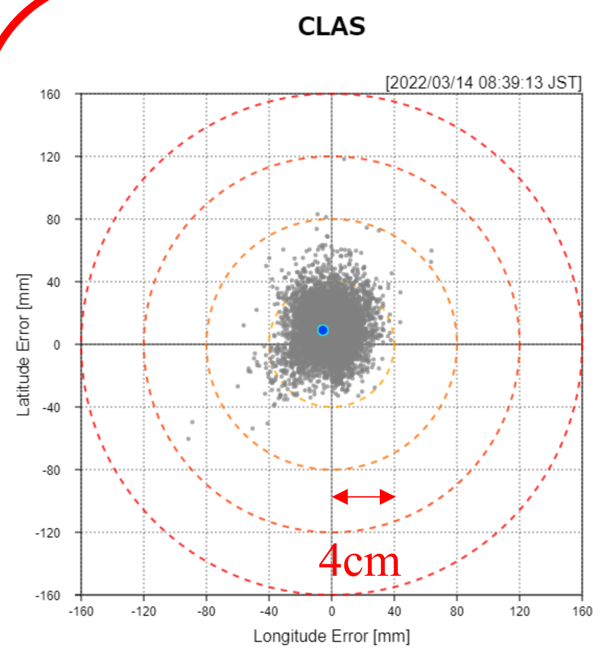
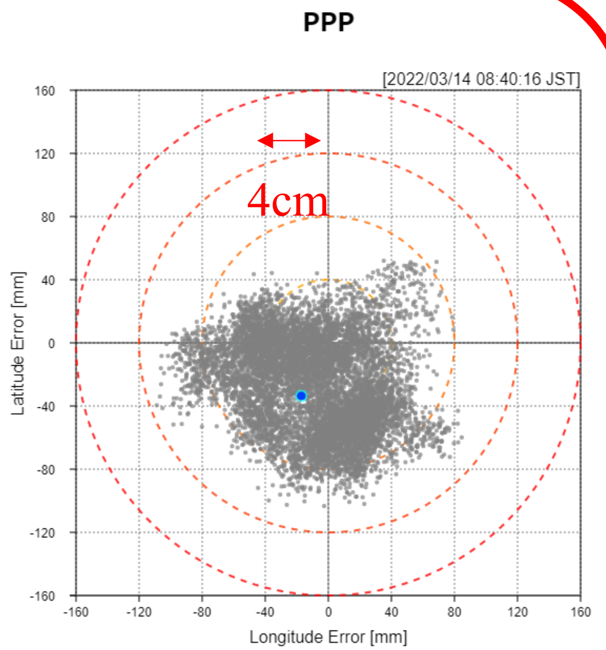
https://www.denshi.e.kaiyodai.ac.jp/gnss_tutor/clas_ppp_slas.html

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

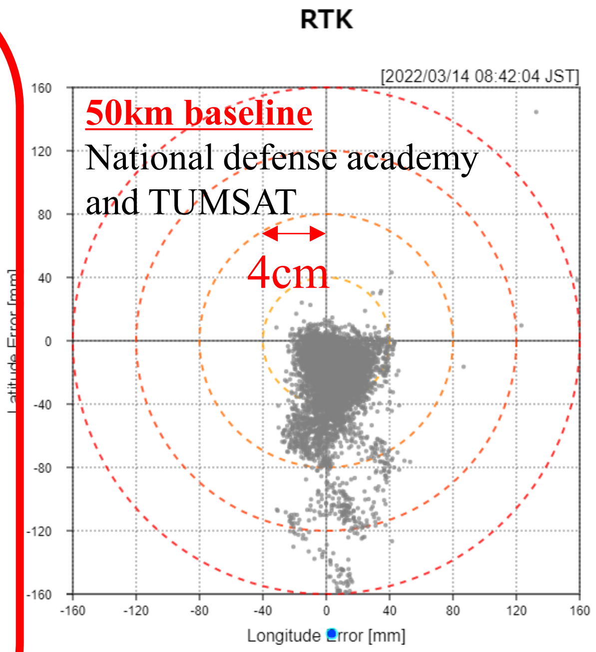




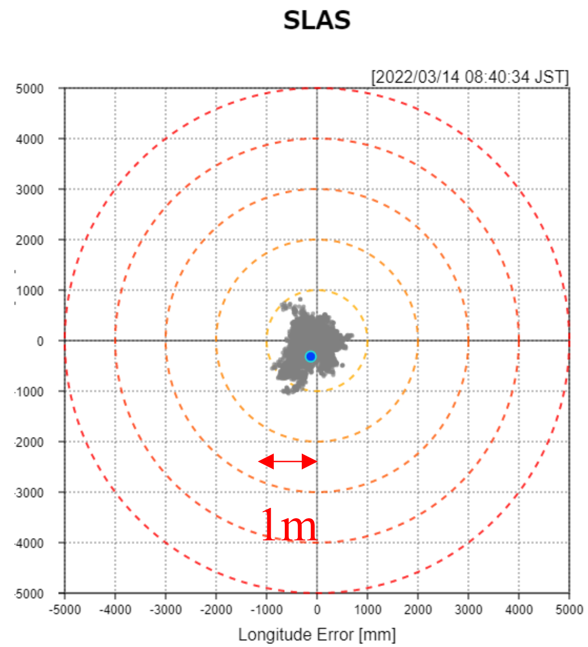
Core
AsteRx4



Magellan Systems Japan
MJ-3008-GM4-QZS



u-blox
F9P



u-blox
F9P

Today's Contents

- Introduction of GNSS precise positioning challenge 2024 in Japan

- Motivation for modified RTKLIB
- Methodology
- Data collection
- Test and Results
- Conclusion

A challenge to compete in positioning accuracy using GNSS and IMU data from urban areas

- We aim to promote GNSS positioning technology and related talent development
- We welcome participation from within Japan and outside the GNSS field
- Students, young engineers, and of course, established experts are all welcome
- Serves as a benchmark through open datasets
- A successful example: Google's Smartphone Decimeter Challenge

Rules

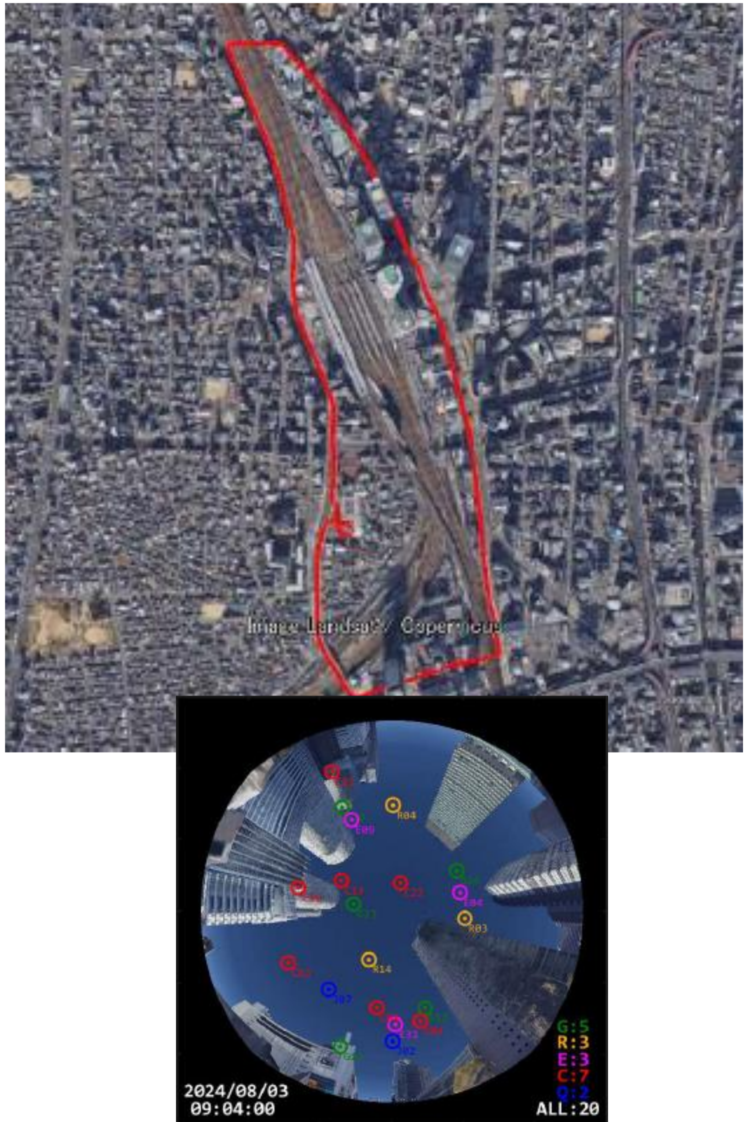
- Vehicle equipped with GNSS navigates urban areas
- Three runs in Tokyo + three runs in Nagoya
- Accuracy evaluated using GNSS/INS integrated system (Applanix POS/LV) as reference
- Estimates three-dimensional position of GNSS antenna mounted on vehicle
- GNSS data provided in RINEX format, assuming real-time processing
- Filtering only in the forward direction
- Evaluation: Competing on accuracy based on the percentage of distances where 3D error is under 50cm
- Algorithm feedback using scores from public data
- Ranking determined using private data with undisclosed scores

Data sets

- Newly released IMU data
- GNSS: 5Hz, Septentrio mosaic-X5, L1+L2+L5
- IMU: 100Hz, acquired via AsteRx SBi3 Pro+
- GPS time stamp included (time synchronized)
- IMU: Analog Devices, ADIS16505-2
- Using Kaggle as the competition platform
- World's largest machine learning competition platform

Nagoya data sets

Nagoya Station Area
Wide roads but tall buildings



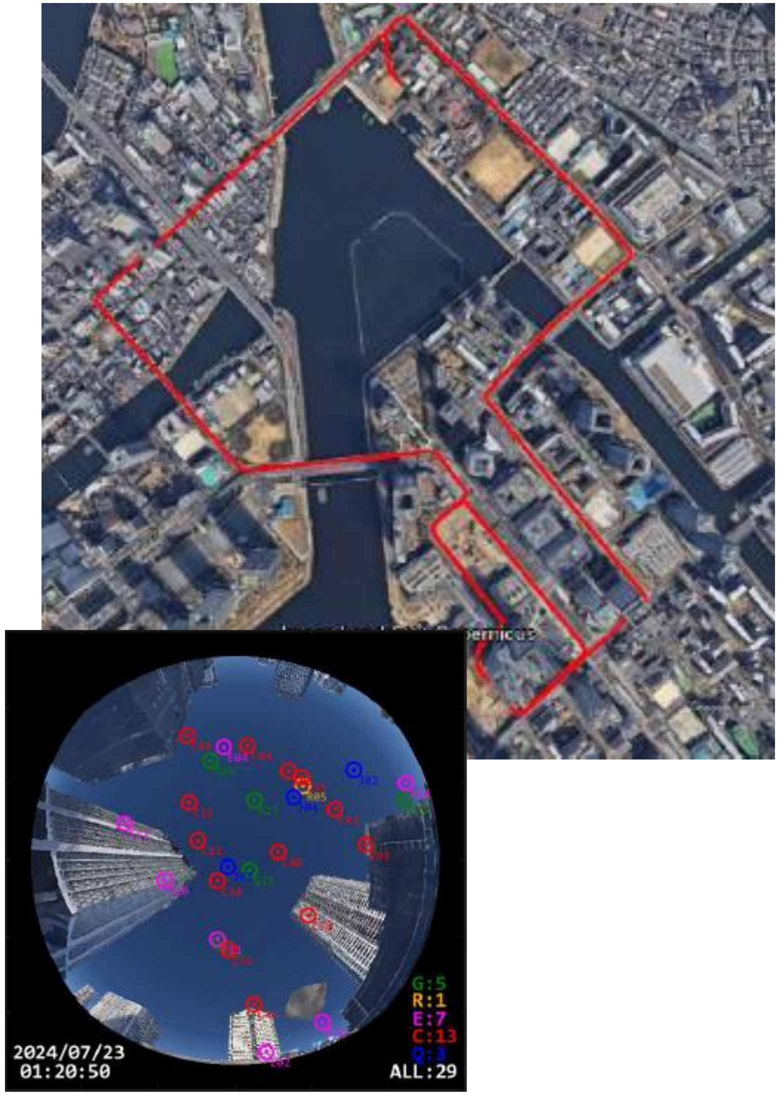
Around Nagoya Station
Narrow roads

Sakae area
Limited overhead visibility

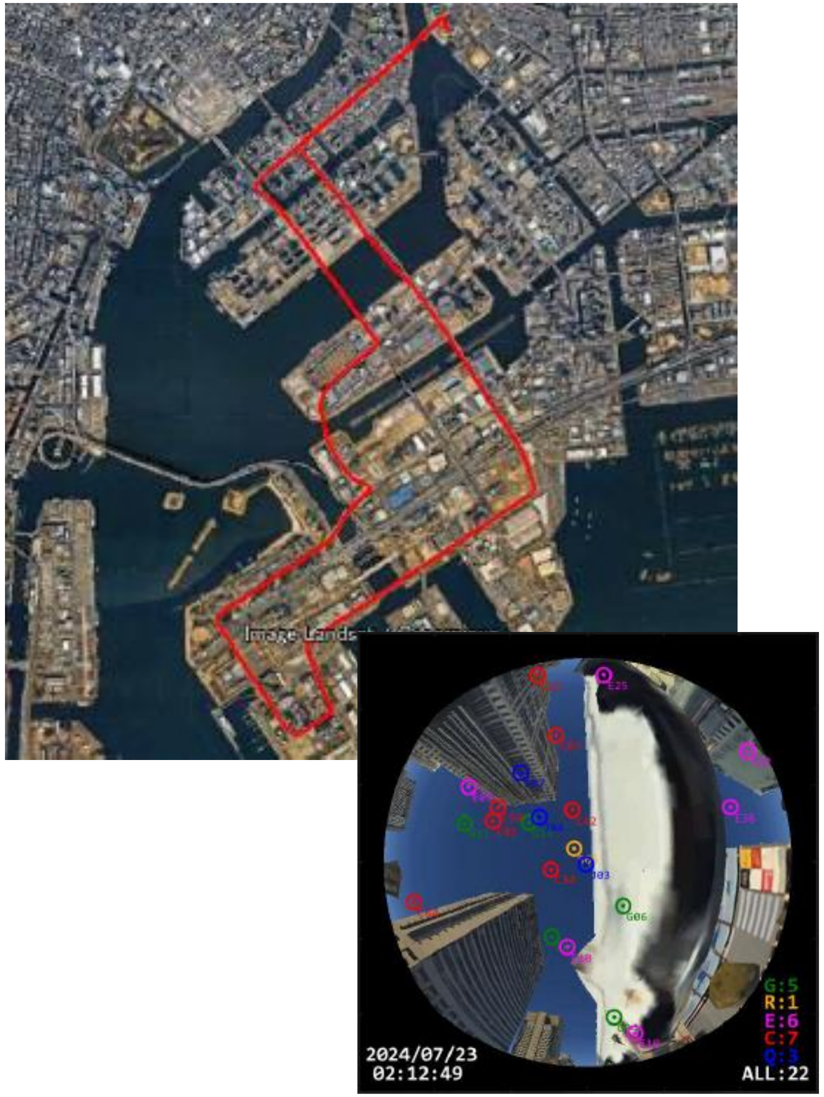
Tokyo data sets

TUMSAT-Tokyo Station
Wide roads but tall buildings

Around Toyosu Station
Dense + semi urban



TUMSAT-ODAIBA
Relatively open sky



OPEN Datasets

- GitHub
- github.com/taroz/PPC-Dataset

- Please feel free to use this for benchmarks and research
- Urban GNSS (5Hz) and IMU (100Hz) data
- Includes position and attitude reference

Top3 Scores

1 : Mr. Inoue (Turing)

Public：78.7% (1位) Private：**85.6%** (1位)

2 : Mr. Okada/Ando/Fukuhara (TUMSAT)

Public：77.6% (3位) Private：**80.3%** (3位)

3 : Dr. Takanose (AIST)

Public：71.6% (6位) Private：**78.0%** (4位)

Evaluation: Competing on accuracy based on the percentage of distances where 3D error is **under 50cm**

Performance of commercial receiver in Tokyo (same as challenge data)

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* Some epochs over several meters (wrong fix)

	X5 （Septentrio）	F9P （u-blox）
1 TUMSAT-Tokyo station	62.7%	failure
2 Around Toyosu	80.0%	72.9% （*）
3 TUMSAT-ODAIBA	82.6% （*）	80.4% （*）
4 TUMSAT-Tokyo station	66.5%	53.4%
5 Around Toyosu	71.0%	77.2% （*）
6 TUMSAT-ODAIBA	74.1%	80.0% （*）
	Average 72.8%	Average 72.8%

Actually, performance in Nagoya is 10-15 % lower than its in Tokyo.

Performance of Modified RTKLIB

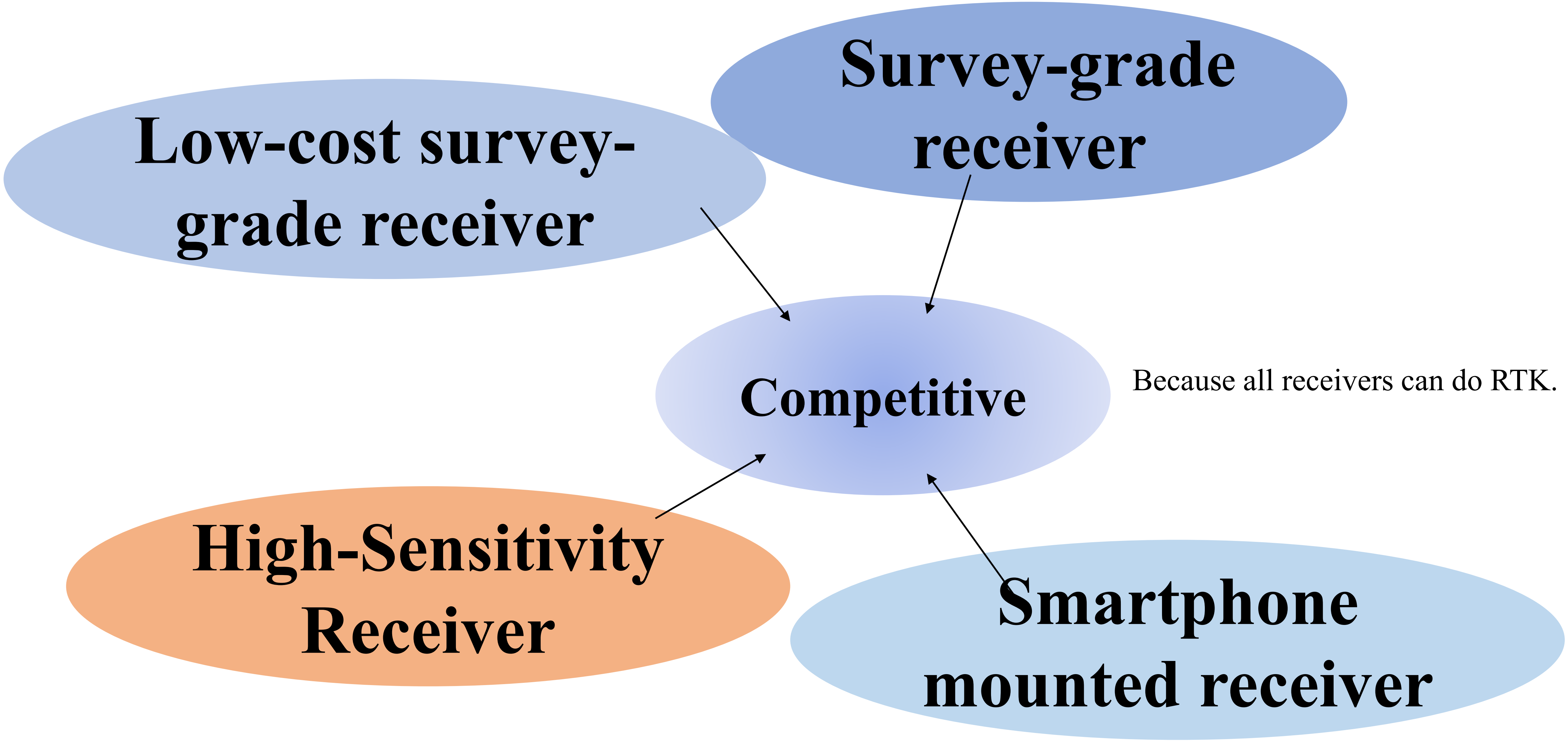
We have evaluated the fix rate of RTK using observation data from X5 and F9P. The fix rate using "TUMSAT-Tokyo station" data sets are as follows.

c	X5（septentrio）	F9P（u-blox）
1 TUMSAT-Tokyo station	62.7% → 81.5%	Failure → 69.0%
4 TUMSAT-Tokyo station	66.5% → 78.5%	53.4% → 57.1%

Modified RTILIB completely outperforms the commercial receiver, and the observation data of X5 is much better than that of u-blox in terms of the number of usable satellites.

Modified RTK-GNSS for Challenging Environments
Sensors **2024**, *24*(9), 2712; https://doi.org/10.3390/s24092712

Competition among GNSS receiver manufacturers serving various target segments



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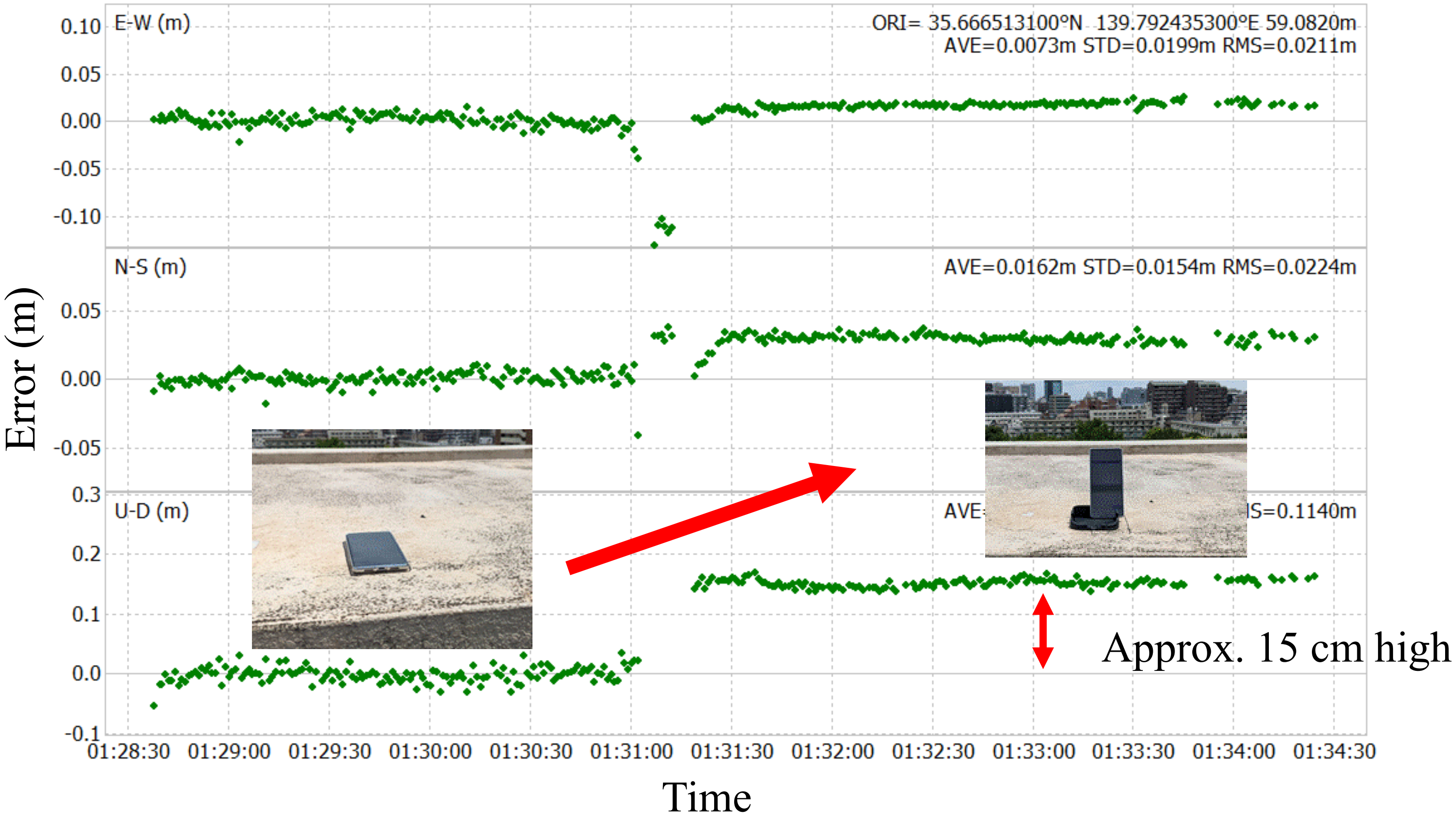
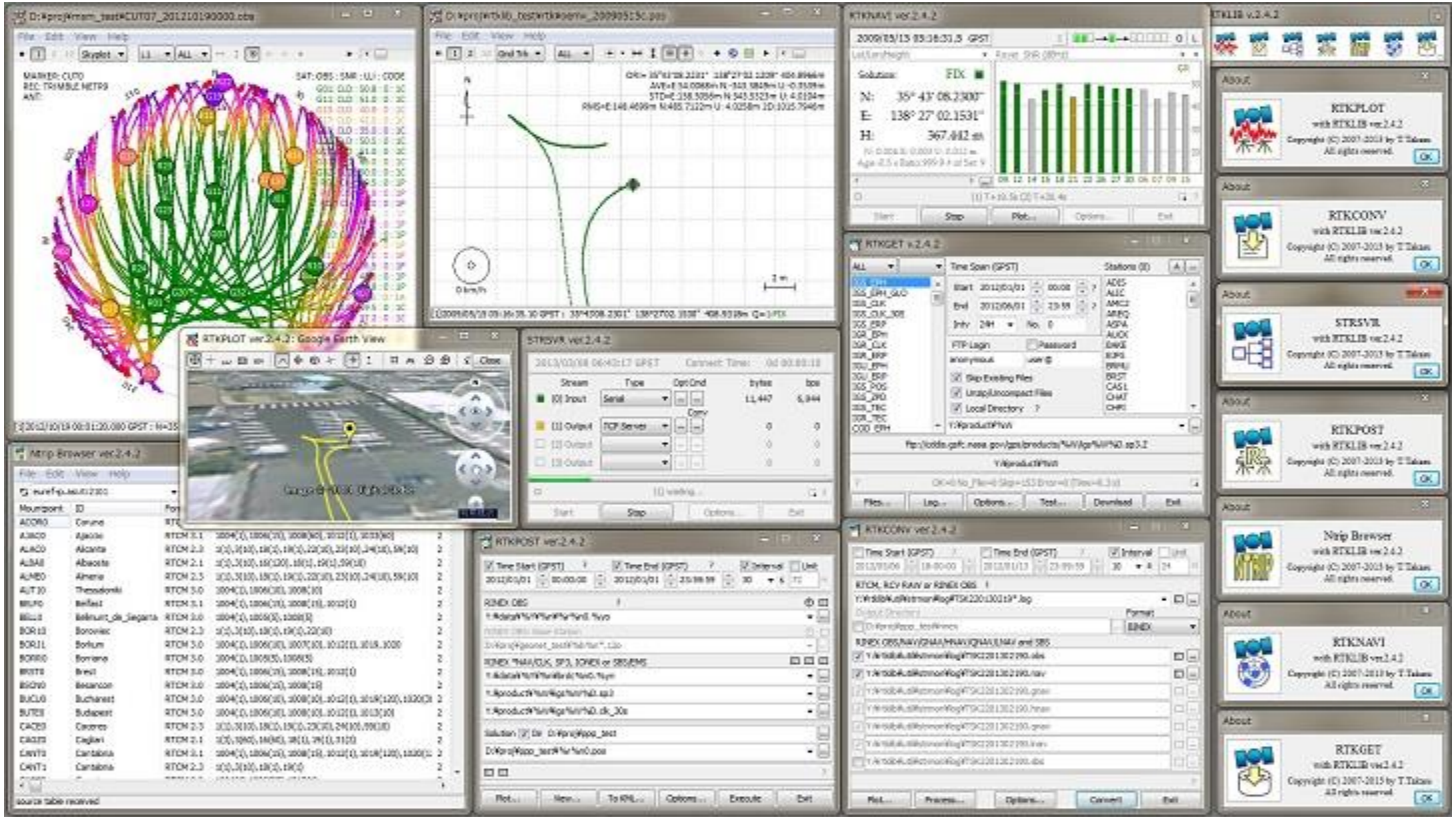
Smartphone stand-alone testing

RTK-GNSS using Pixel6pro
(L1, GQEB, 30dBHz, Lab’s software)



RTKLIB（2006~）

The developer is
Mr. Tomoji Takasu.



Motivation

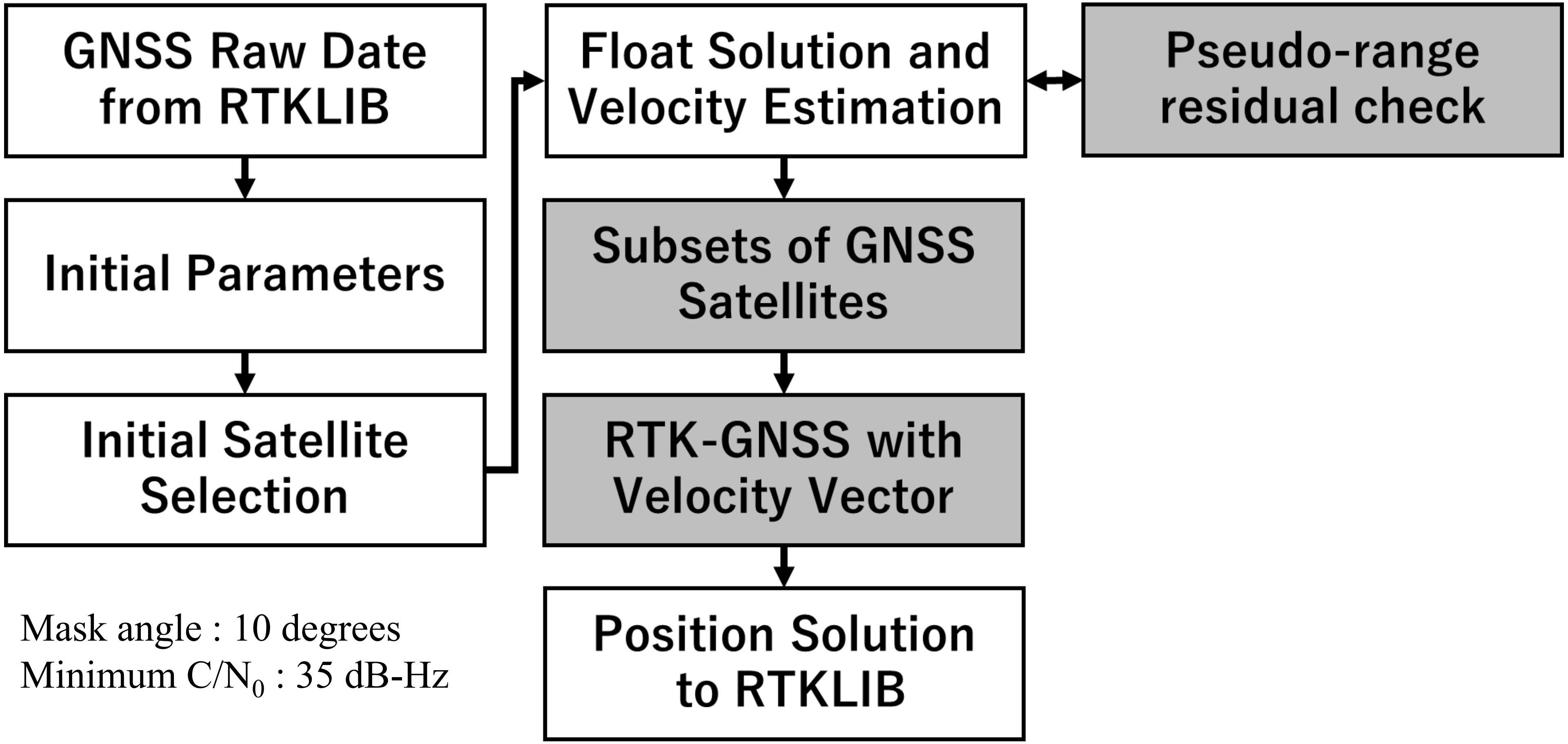
- The RTK performance of **commercial receivers** has improved owing to the commercial availability of low-cost dual-frequency receivers since around 2018.
- Little by little, differences in performance are being seen especially in the case of **urban areas**.
- **rtklibexplorer** has contributed to fill in the gaps in this situation.
- Here, we describe an improved algorithm for RTK, particularly for vehicles in urban areas, and present the experimental results by comparing the RTKs of RTKLIB, rtklibexplorer, and a typical low-cost RTK receiver

Three methods for the improvement

1. Satellite selection based on Pseudo-range/Doppler residuals
2. Use of GNSS velocity for float solutions
3. Subsets of GNSS satellites
4. Recalculating ambiguities

- These are **conventional methods**, but it is effective to improve the RTK performance.

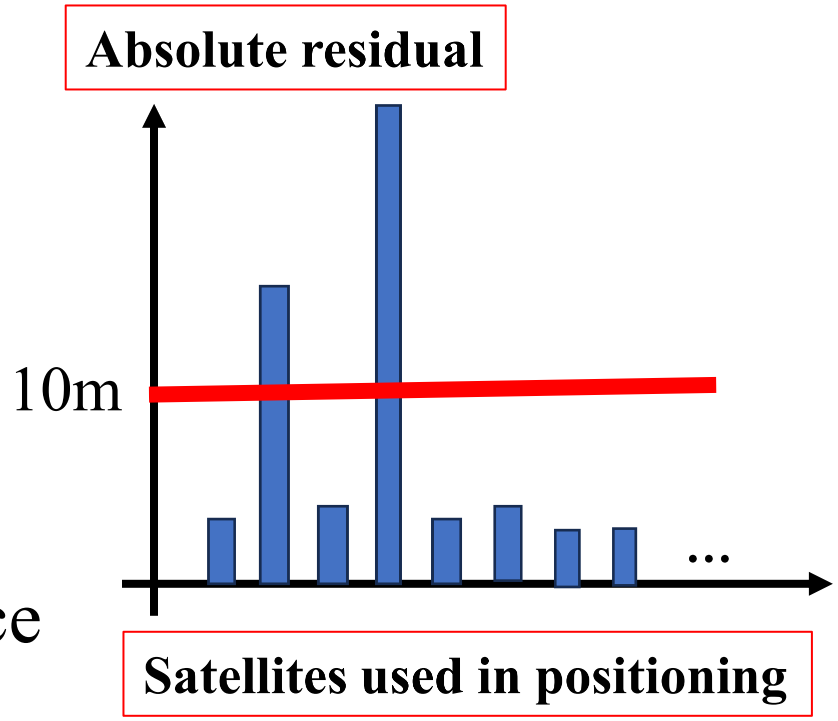
Flowchart of methodology



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

Pseudo-range residual check

- The residuals of the satellites were checked using the least squares method.
- If the absolute residual of the satellite was at its maximum and was over approximately **10 m**, the satellite was repeatedly removed from positioning, provided that the HDOP was lower than 10.
- The maximum iteration number is set.
- If you don't want to remove the satellite, we can reduce the weight the satellite in positioning.
- This method is not optimal in that the residuals themselves are affected by the error.



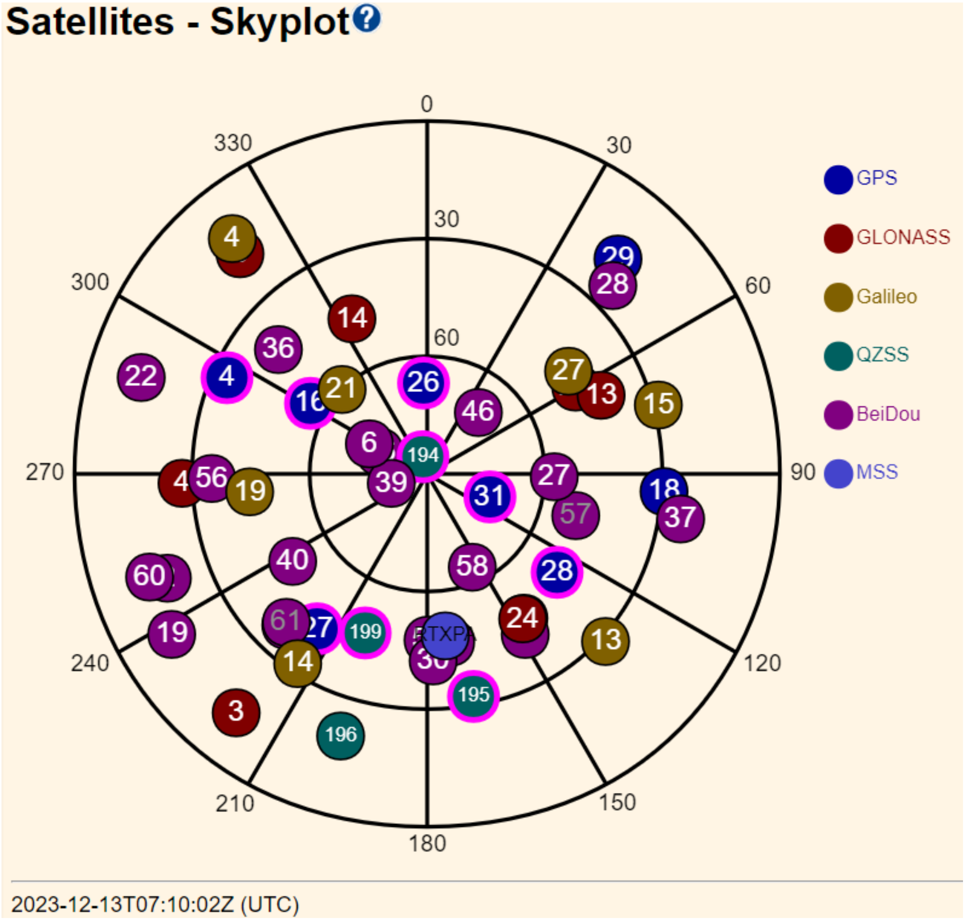
Doppler frequency residual check

- Similar to pseudo-range residual checks, residuals are checked during velocity estimation. Satellites exceeding the threshold (about 1-5Hz) are either excluded or adjusted using weights.
- Velocity information is recently very important because we rely on velocity more than pseudo-range in terms of accuracy (highly resistant to multipath errors).

Subsets of GNSS satellites

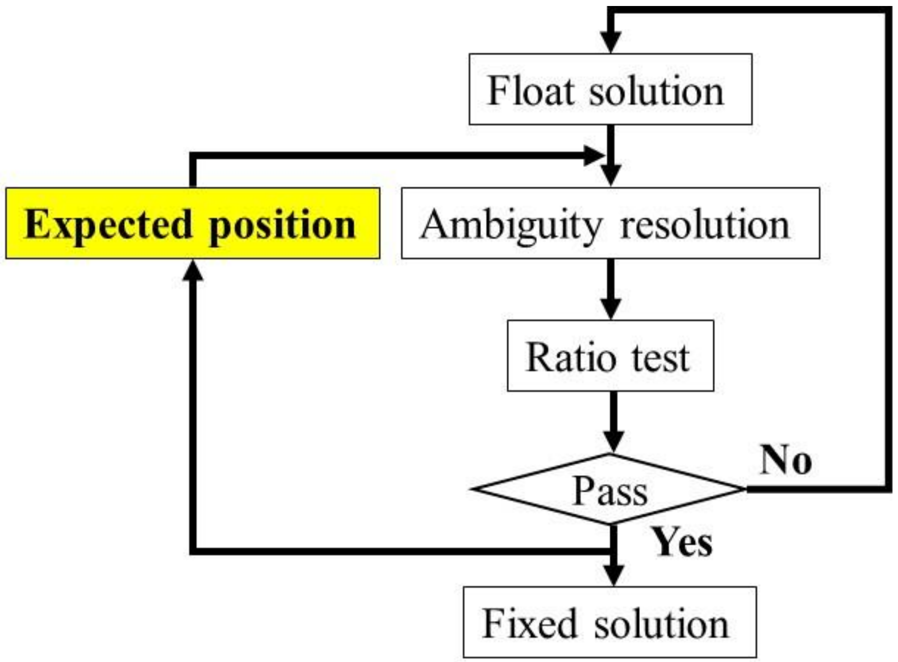
- We are now on multi-GNSS era.
- First of all, we use all 5 satellites (GPS/GLONASS/GALILEO/BDS/QZSS).
- If we can't get RTK fix solution, we re-select other satellite systems.
- The order is as follows.
- GREBQ→GEBQ→GREB→GEQ→GQ

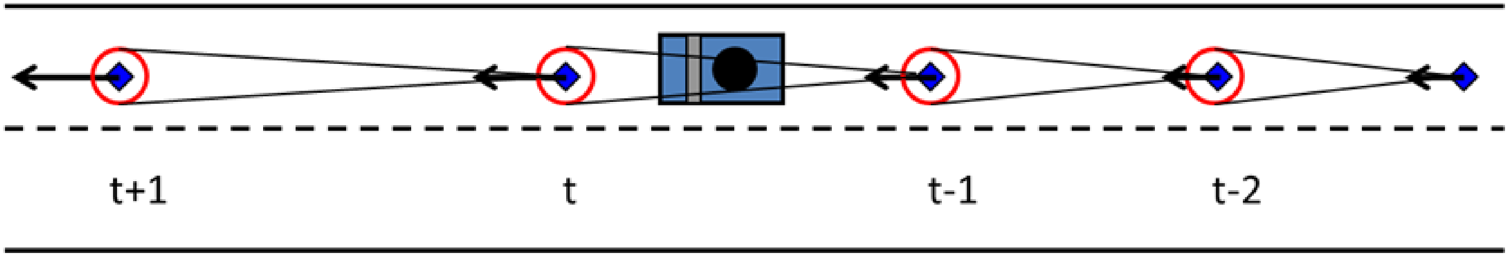
If you have nice PAR, you had better use it.
(PAR : partial ambiguity resolution)



Over 60 degrees, 8 satellites are available !

Ambiguity Resolution using Velocity Information





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

Interval = 1.0 sec

The **expected position** is the previously fixed position, updated by adding half the present velocity estimate and half the previous velocity estimate.

The reliability of the previously fixed position is important.

Dead reckoning using velocity information

- The previous slide used velocity information only when FIX was achieved in the previous epoch to generate the FLOAT solution for the next epoch.
- This approach would give up if FIX was not achieved. Since velocity information fundamentally utilizes Doppler frequency (which is close to carrier phase accuracy when the carrier phase is locked), we do not give up after one attempt.
- Even when FIX is not achieved, we simultaneously compute a FLOAT solution by integrating the velocity vector over a certain number of epochs.
- We use this FLOAT solution to search for the correct FIX solution.

The rate of the wrong fixing using different data sets

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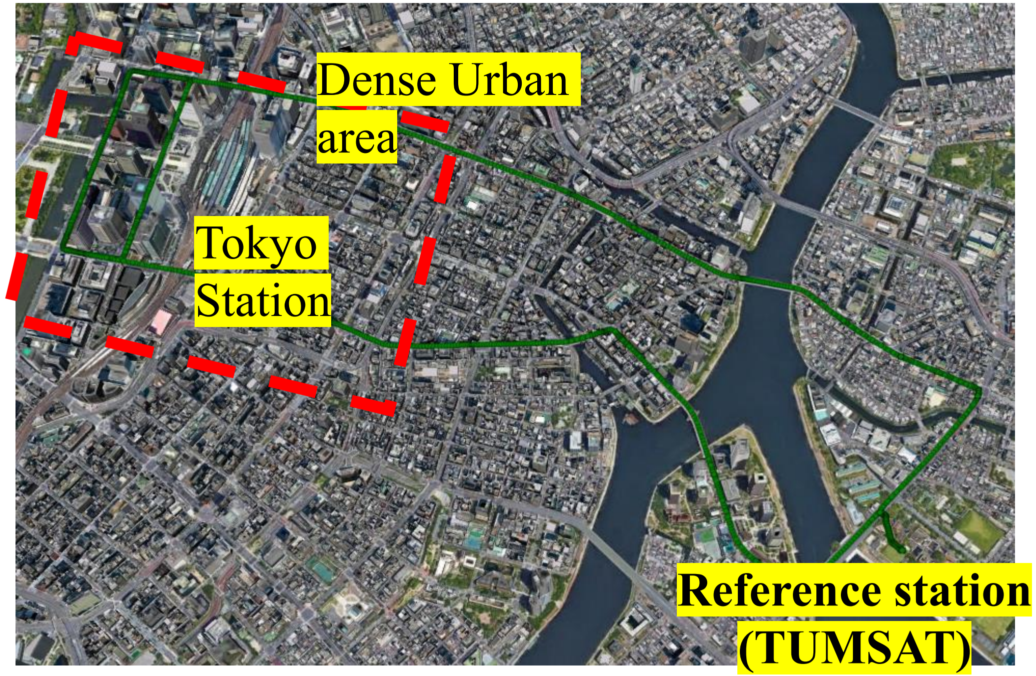
ION presentation in 2022

Result (Lap1)	Fix rate/miss Fix rate
Fore antenna (F9P)	69.9% / 0.26%
Aft antenna (F9P)	70.4% / 1.09%
Fore antenna (our laboratory)	60.3% / 0.49%
Aft antenna (our laboratory)	65.3% / 0.16%

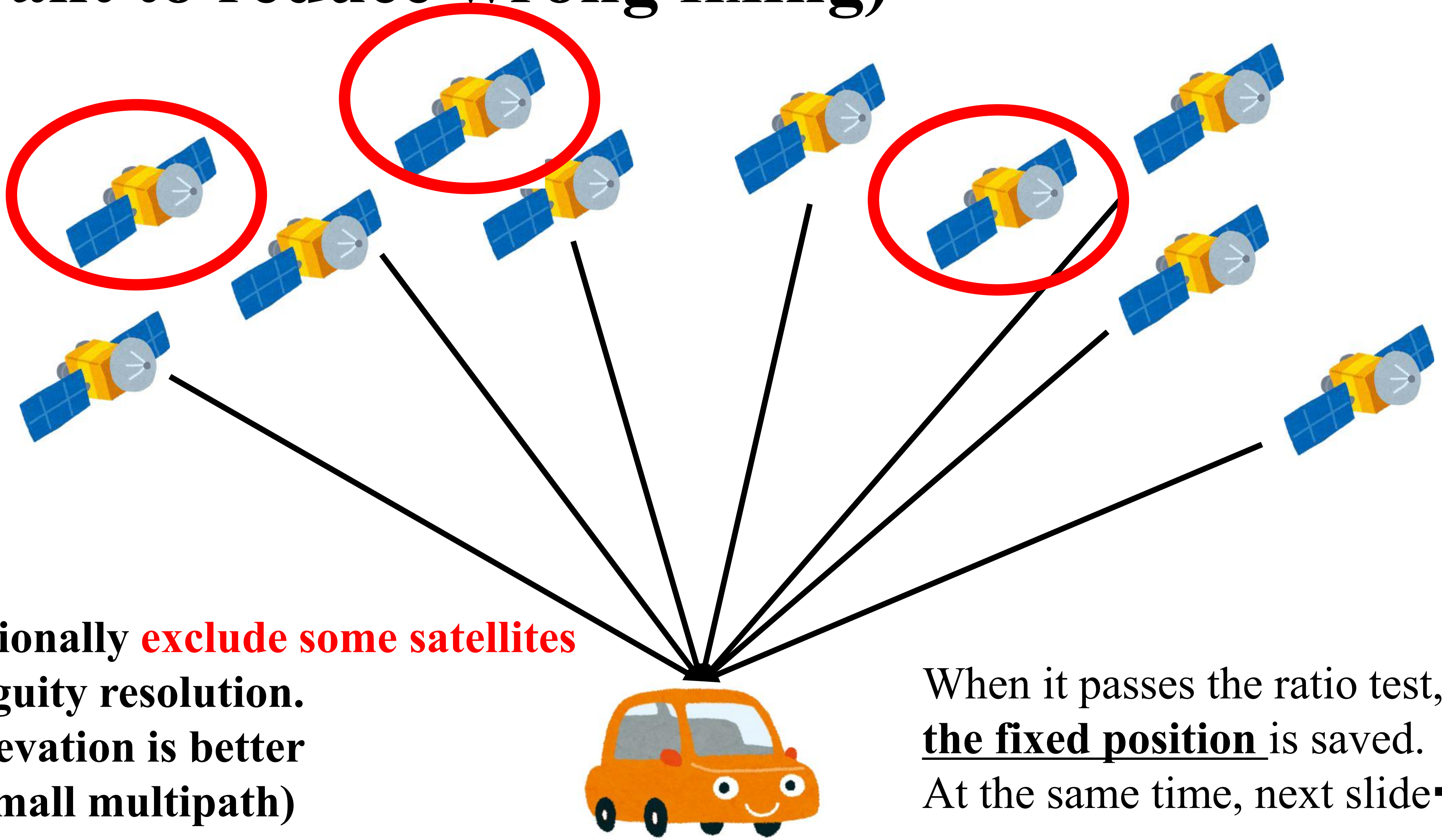
Result (Lap2)	Fix rate/miss Fix rate
Fore antenna (F9P)	53.2% / 1.63%
Aft antenna (F9P)	57.1% / 0.13%
Fore antenna (our laboratory)	46.3% / 0.88%
Aft antenna (our laboratory)	36.3% / 0.16%

Result (Lap3)	Fix rate/miss Fix rate
Fore antenna (F9P)	48.3% / 3.28%
Aft antenna (F9P)	58.0% / 0.39%
Fore antenna (our laboratory)	56.4% / 0.69%
Aft antenna (our laboratory)	54.2% / 0.57%



Basically, below 1.0 % has been achieved but it still needs improvement.

Reliable Ambiguity Resolution (we want to reduce wrong fixing)



We intentionally exclude some satellites
For ambiguity resolution.
(higher elevation is better because small multipath)

When it passes the ratio test,
the fixed position is saved.
At the same time, next slide➔

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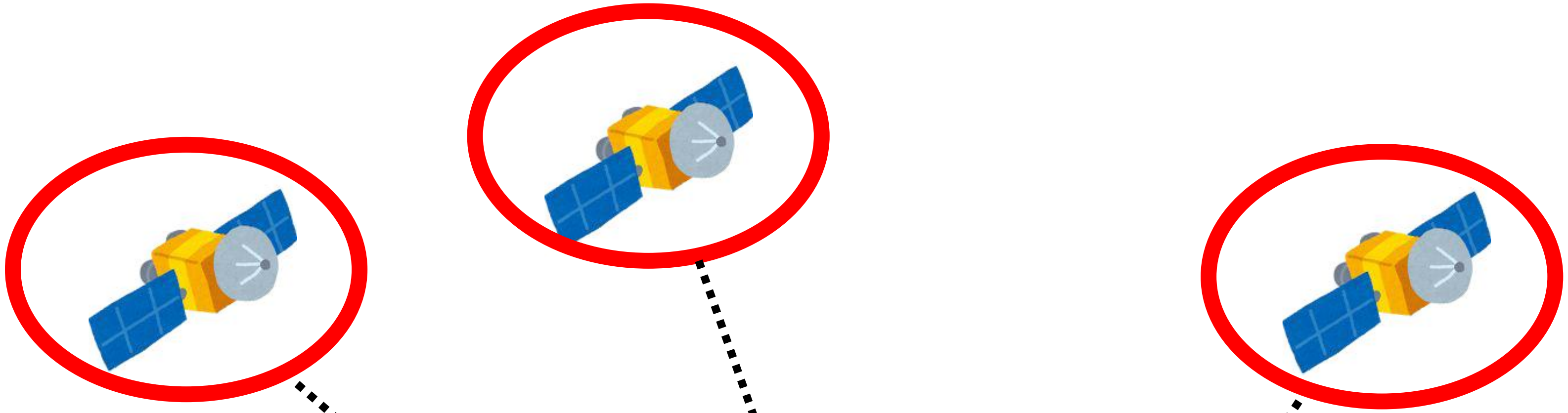
We wan to reduce the wrong fix as much as possible.



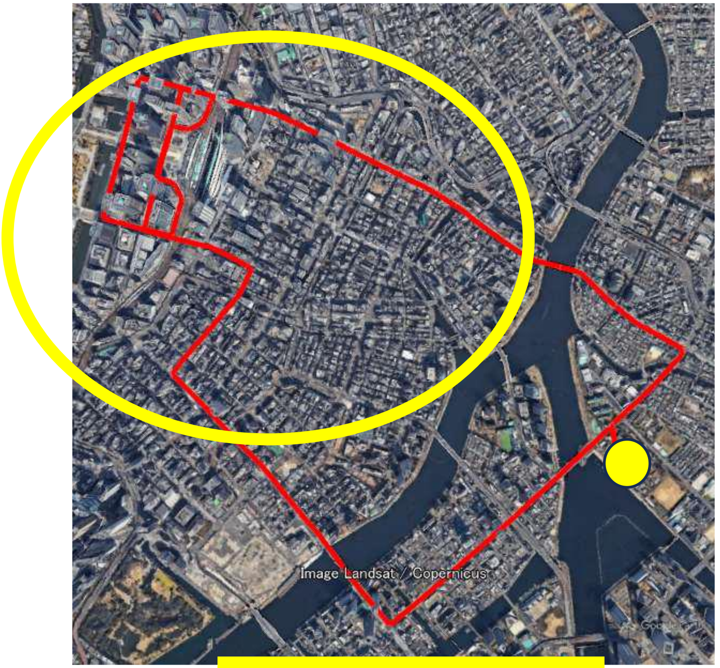
Using the fix solution, we take a double phase difference measurement on a group of satellites not previously used.
Since we already know the expected precise baseline,
we determine whether the fix solution is correct by checking
if that double phase difference is close to an integer value.

If the estimated fixed position is correct,
the double phase difference should be
an integer value.

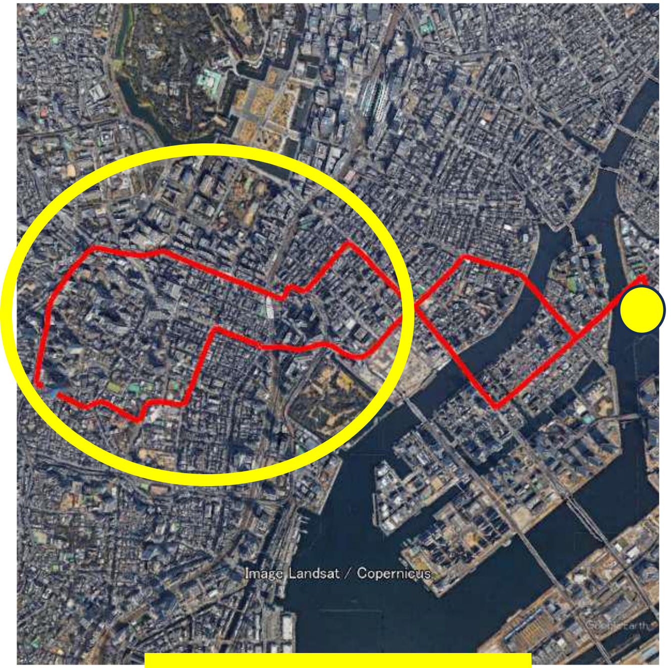
This car already knows
the expected precise position !

Data collection (2023)

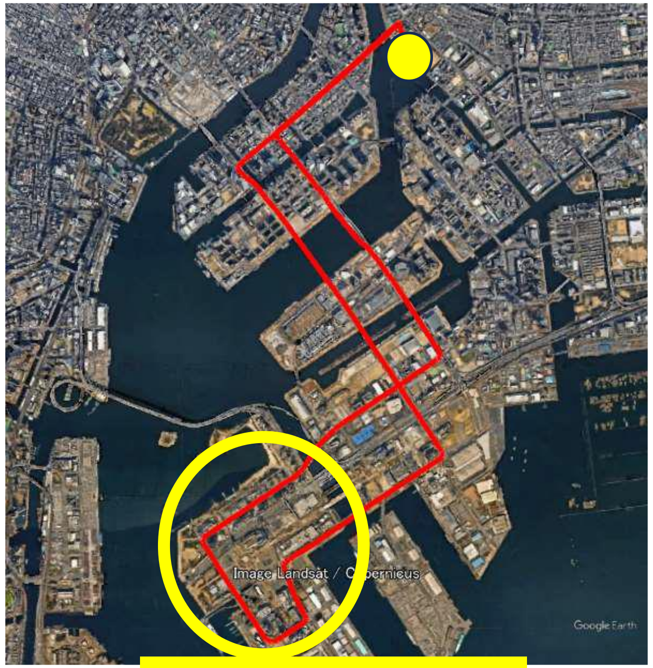
Sensor	Model name
GNSS Receiver (base and rover)	u-blox F9P
GNSS Antenna (rover)	Trimble AT1695
GNSS Antenna (base)	Trimble Zephyr 2 Geodetic
Reference Position	POSLV620 (post-processed)



Test1 3,360 s



Test2 3,088 s

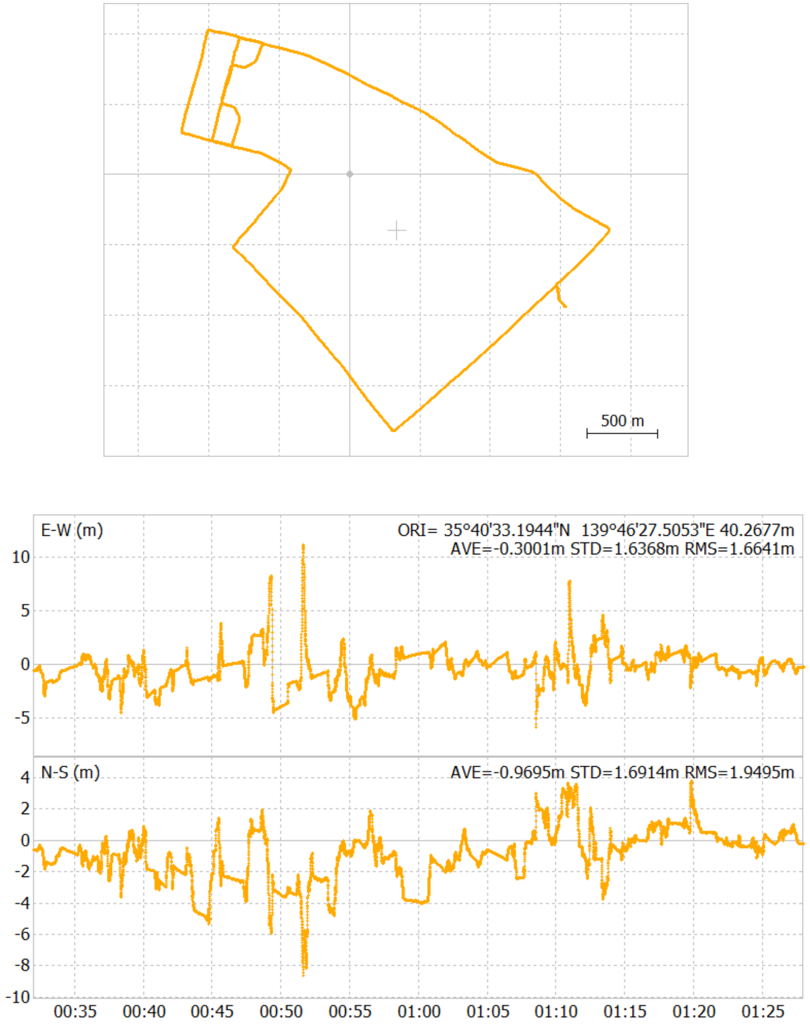


Test3 2,852 s

Data analysis

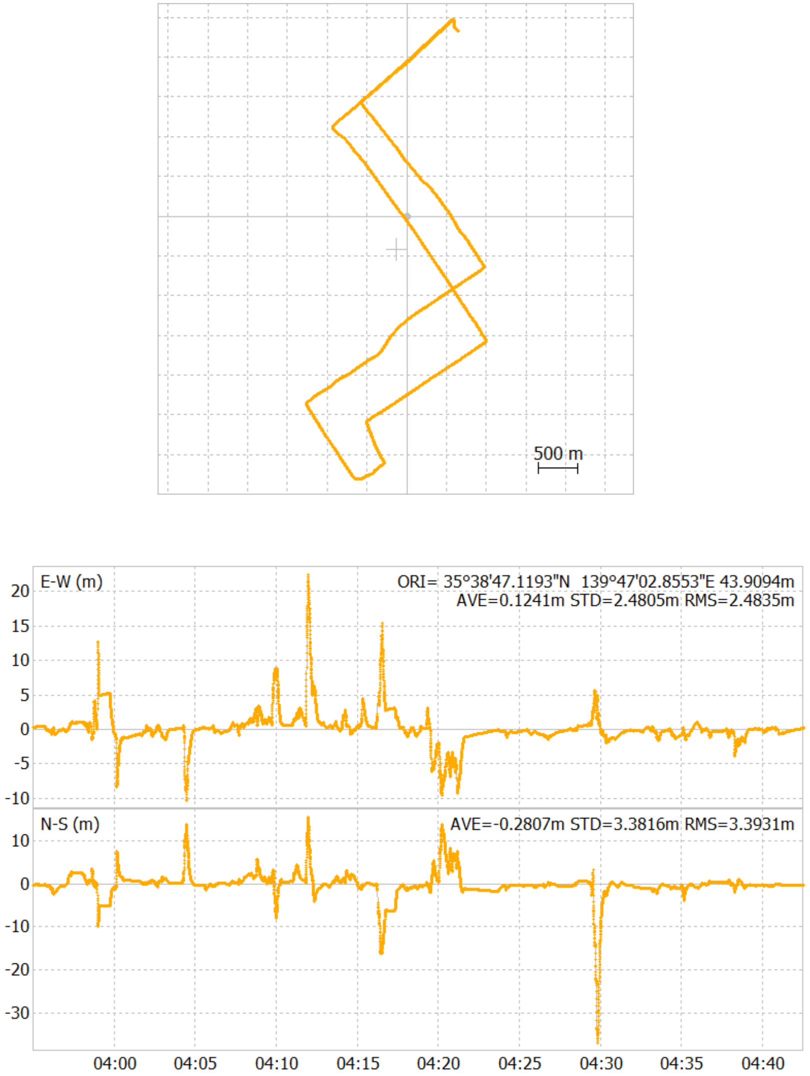
- Raw GNSS data of **dual-frequency** observations were post-processed using the algorithm mentioned above.
- The processing is **only forward** and can be used in real time.
- The settings of the important parameters were the same for all the tests. The mask angle was set to **10°.** The minimum carrier-to-noise ratio was set to **35 dB-Hz**. The threshold for the pseudo-range residual check was set to **10 m**.
- First, the test results of the float solutions (DGNSS+Velocity) are introduced. Second, the test results of the RTK-GNSS are introduced in terms of both the **fix rate** and accuracy (**Horizontal 2D RMS**).
- **We don’t change parameters at all.**

Test results of float solutions



Test1(dense)

Test2(very dense)



Test3(normal)

Comparison with commercial receiver

Horizontal 2DRMS comparisons between Modified RTKLIB and commercial receiver

Test number	Modified RTKLIB	Commercial receiver (u-blox F9P)
Dense urban	5.12 m	11.88 m
Very dense urban	5.68 m	16.45 m
Normal urban	8.41 m	7.97 m

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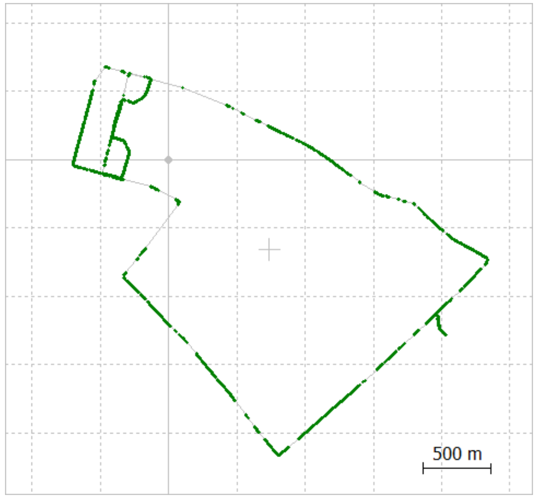
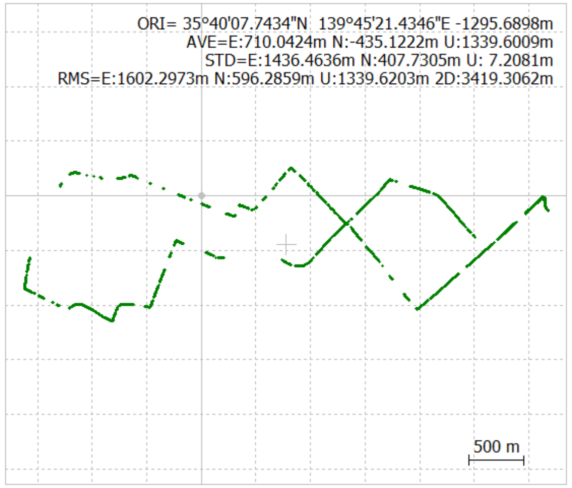
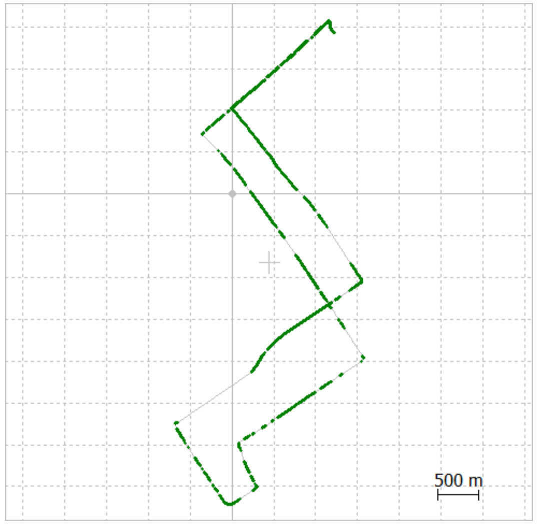
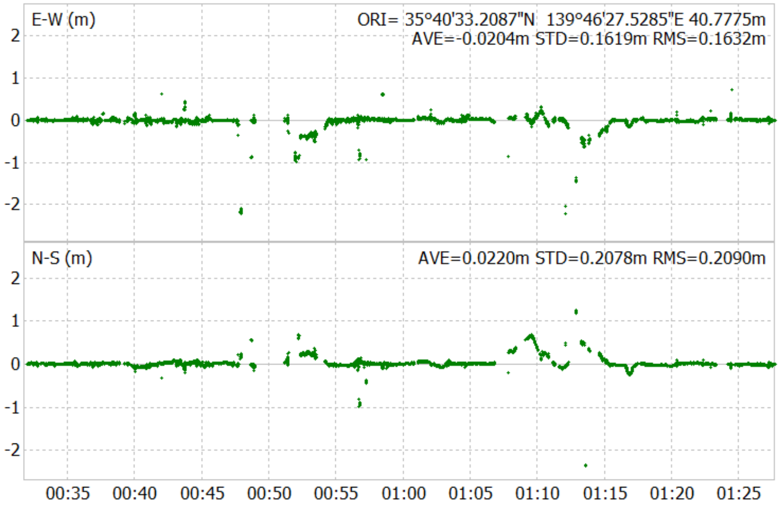
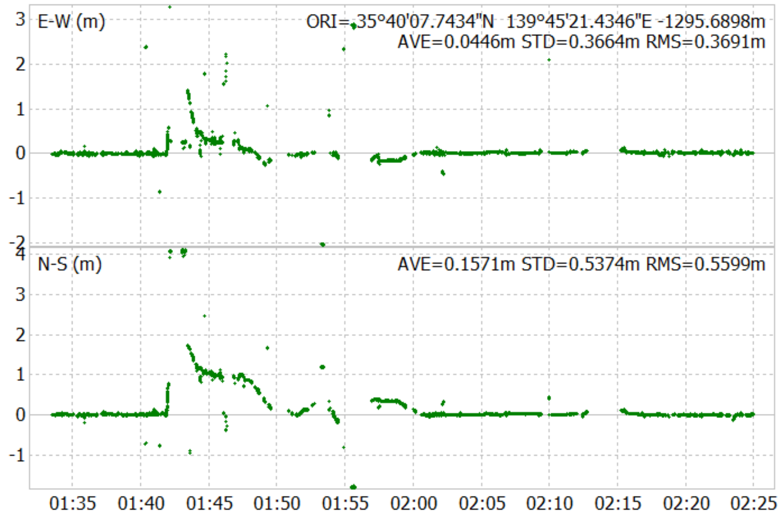
Test results of RTK-GNSS

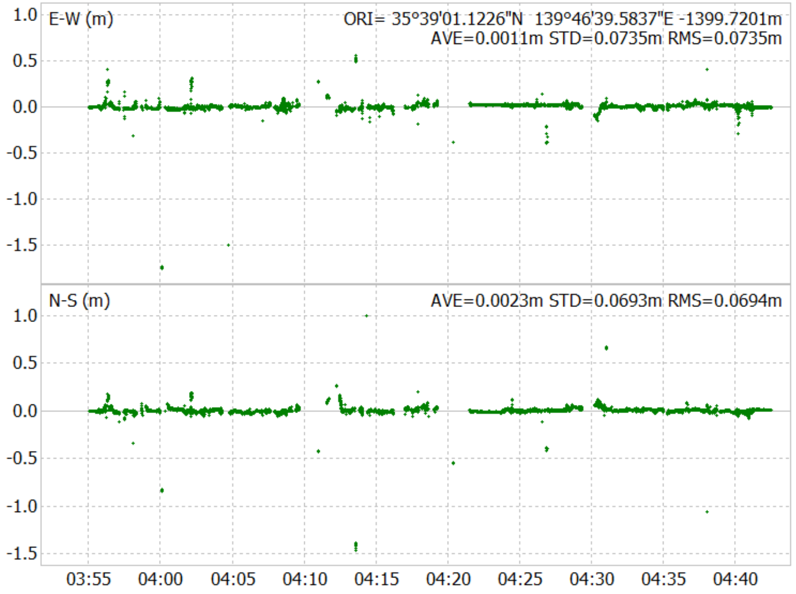




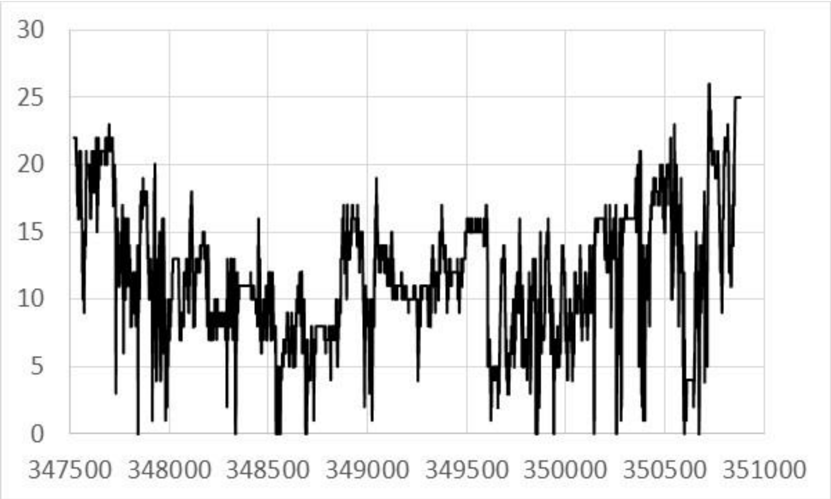








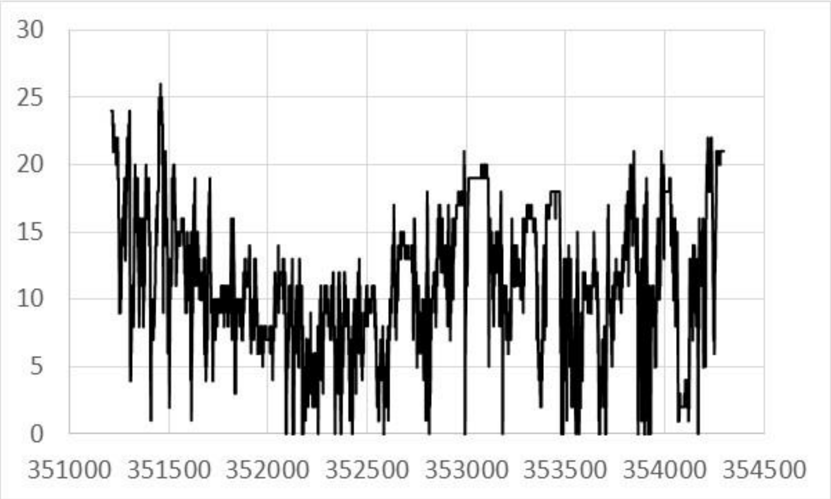
Temporal used satellites for 3 Tests (Dual-frequency carrier phase : valid)



Average number of used satellites

Test1 : **11.6**

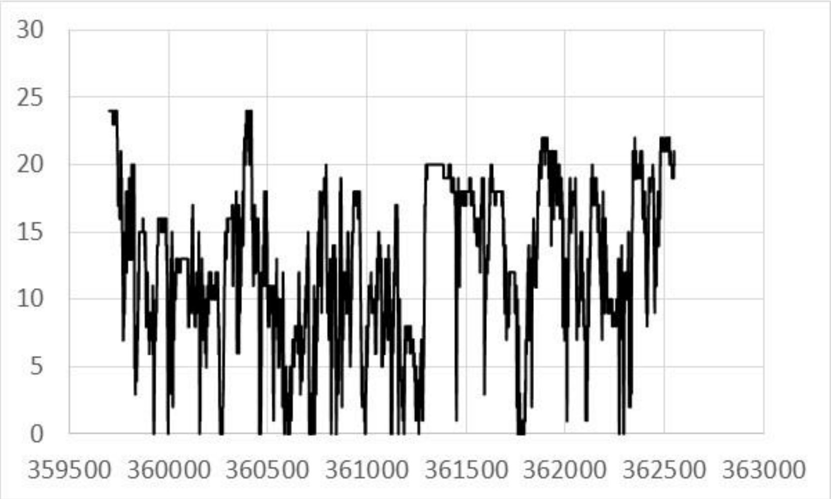
(25.8 for base station)



Average number of used satellites

Test2 : **11.2**

(25.3 for base station)



Average number of used satellites

Test3 : **12.6**

(24.8 for base station)

Comparison with commercial receiver

Test Course	Modified RTKLIB		Commercial receiver (u-box F9P)	
	Fix rate	Horizontal 2DRMS	Fix rate	Horizontal 2DRMS
Dense urban	66.8 %	0.53 m	52.2 %	0.32 m
Very dense urban	58.0 %	1.34 m	47.9 %	0.82 m
Normal urban	67.8 %	0.20 m	74.2 %	0.54 m

Comparisons with RTKLIB/rtklibexplorer

GNSS LAB Tumsat

- 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 Course	Modified RTKLIB		RTKLIB	
	Fix rate	Horizontal 2DRMS	Fix rate	Horizontal 2DRMS
Dense urban	66.8 %	0.53 m	41.1 %	7.69 m
Very dense urban	58.0 %	1.34 m	34.3 %	7.36 m
Normal urban	67.8 %	0.20 m	54.3 %	11.23 m

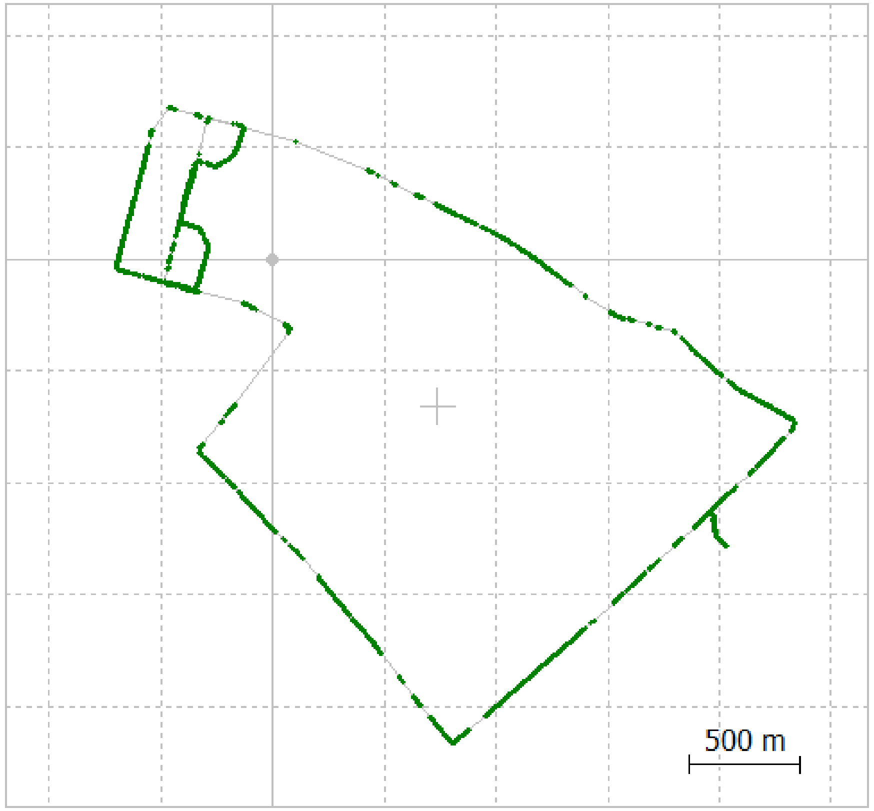
Comparison with rtklibexplorer

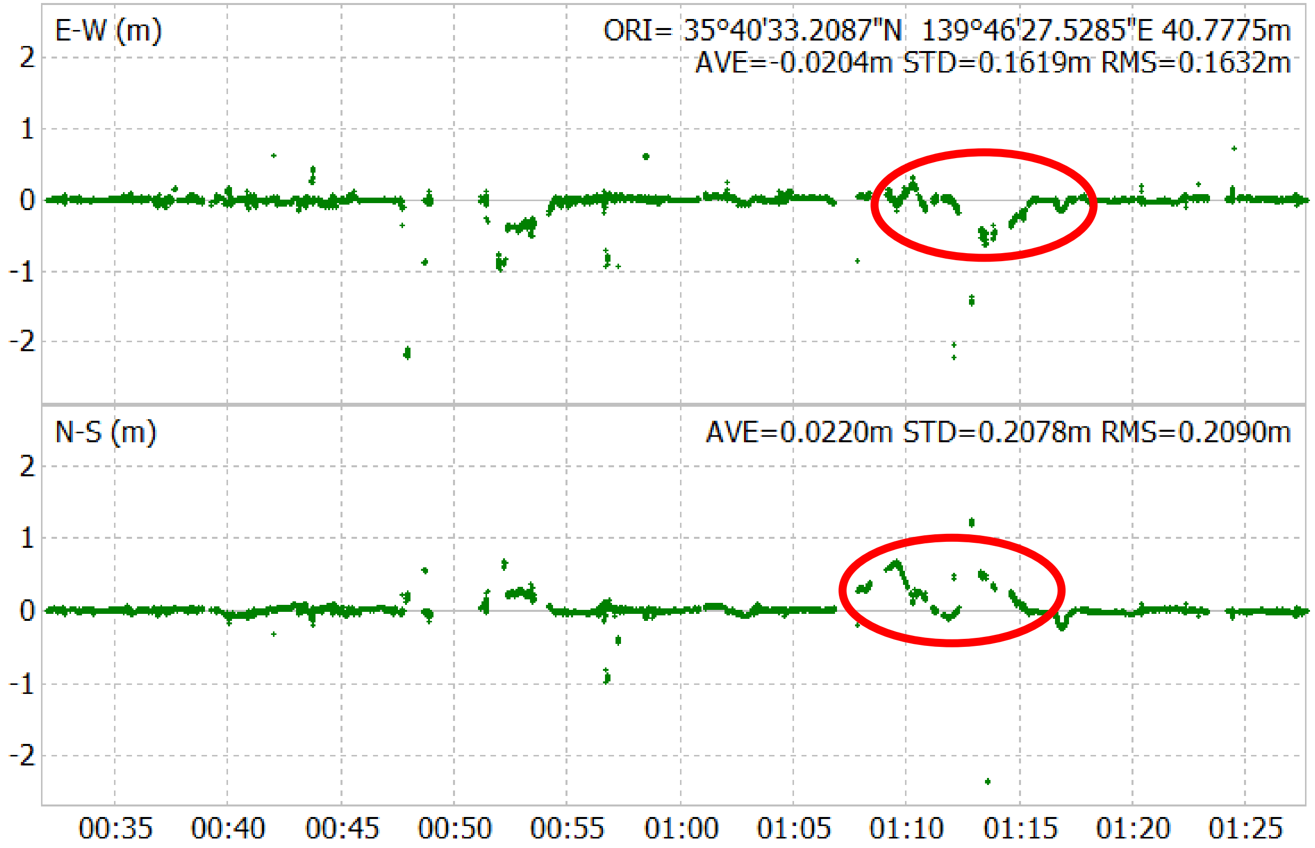
Test Course	Modified RTKLIB		rtklibexplorer	
	Fix rate	Horizontal 2DRMS	Fix rate	Horizontal 2DRMS
Dense urban	66.8 %	0.53 m	64.3 %	1.24 m
Very dense urban	58.0 %	1.34 m	60.8 %	2.35 m
Normal urban	67.8 %	0.20 m	72.5 %	0.39 m

Conclusion

- This paper presented the improvement of the generic and well-known RTKLIB GNSS software.
- RTK-GNSS was improved by applying velocity vectors and selecting satellites with good signal quality before positioning.
- However, the performance of low-cost commercial receivers was also observed to be good, and while our proposed modified RTKLIB was sometimes superior in terms of the fix rate, it was not as accurate.
- We also deduced that the performance could be considerably improved using the open-source rtklibexplorer by determining the optimal setting values.
- In the near future, we plan to evaluate methods to further reduce the wrong fixes of RTK-GNSS and improve the fix rate.

Another future work





POLSV seems to have some errors. These errors are not from RTK results but POSLV.

Any questions and comments ?

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The Meiji Maru – A Symbol of Japan's Maritime Modernization

- The *Meiji Maru* is a historic sailing ship built in 1874 in Glasgow, Scotland, by Robert Napier & Sons. Originally designed as a lighthouse tender, it soon gained national importance when Emperor Meiji used the vessel during his official voyage to northern Japan in 1876.
- After decades of service, the ship was preserved and is now a designated Important Cultural Property of Japan. Today, the *Meiji Maru* is permanently displayed at Tokyo University of Marine Science and Technology, where it continues to inspire students and visitors as a symbol of Japan's maritime education and modernization.