Instantaneous GNSS RTK for vehicular applications with low-cost receivers

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Agenda

- Motivation and Background
- Single-epoch multi-GNSS RTK
- Automobile test under relatively open sky

  -Experiment and Results
- Multipath environment test

  -Experiment and Results
- Sports application – Sprinting RTK

  -Experiment and Results
- Summary

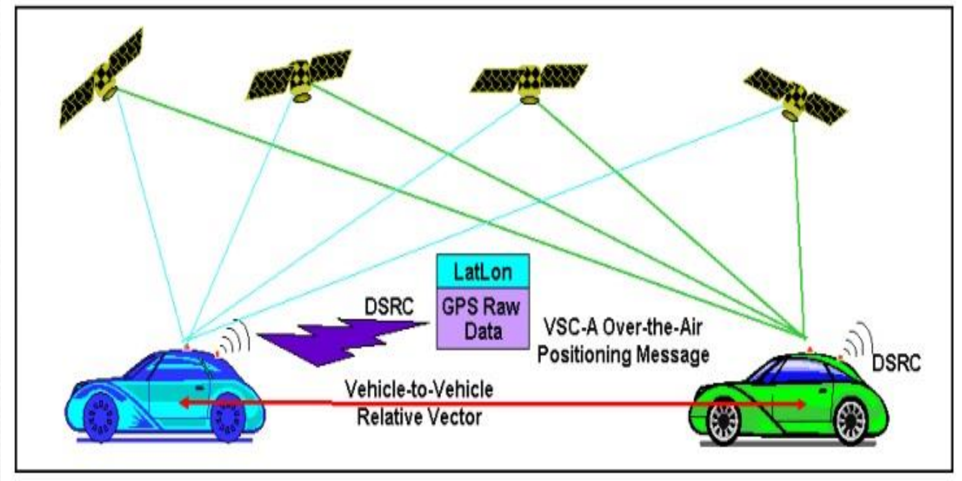
Motivation & Background

- Possible to achieve high precision positioning with RTK-GNSS

- Deployment of DSRC (Dedicated Short Range Communications) for V2V and V2V vehicle safety and mobility applications is in motion

- Prospective accuracy for safety apps under Intelligent Transportations Systems (ITS) like lane recognition is to be under 1m with continuous positioning

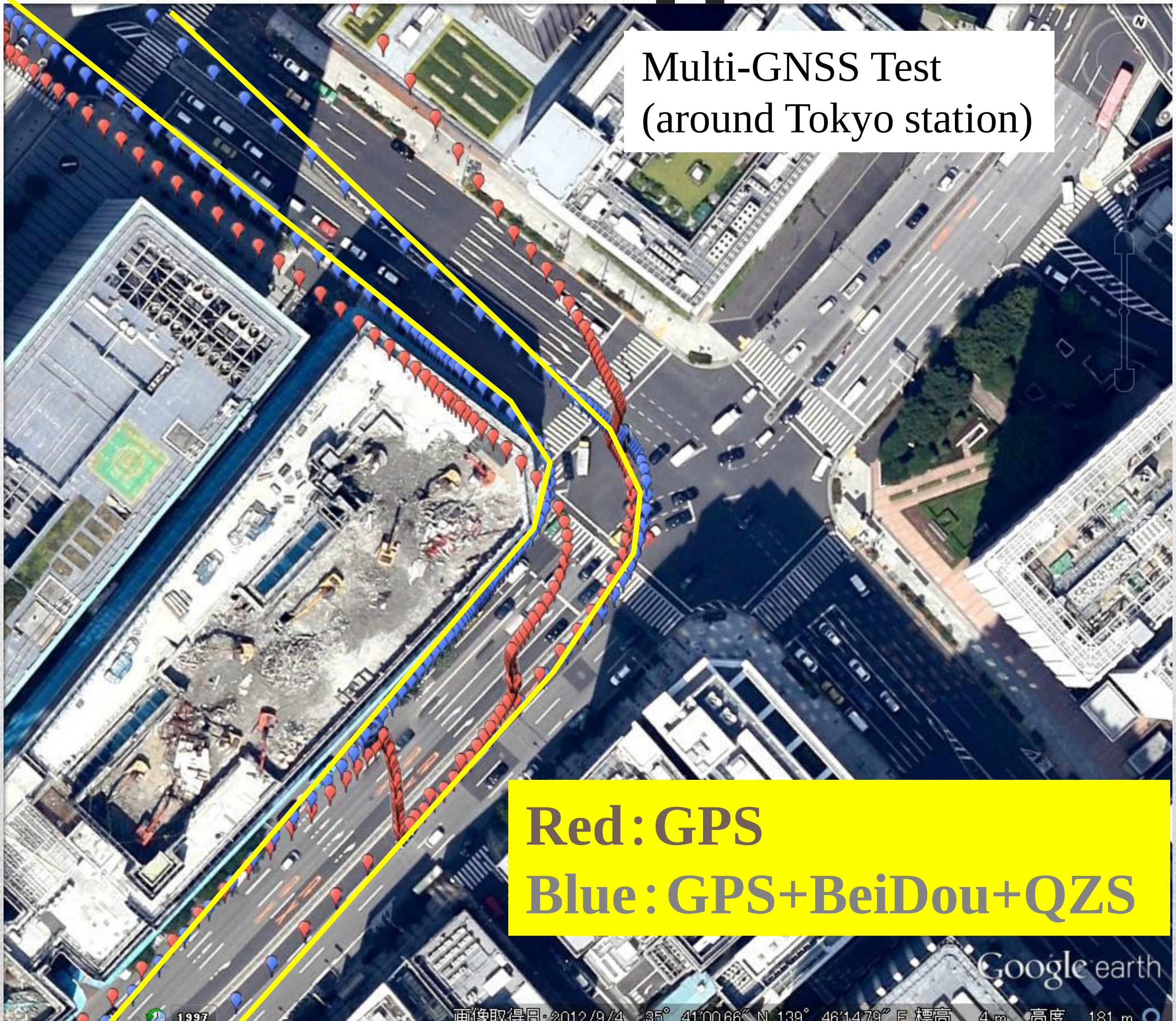
- DSRC standard also encompasses bicycles, pedestrians etc.



Dedicated Short Range Communication (V2V)

[SURFACE VEHICLE STANDARD- J2735T]

Multi-GNSS approach



GPS-only vs. GNSS:

- using only the GPS-L1 signal, the FIX rate of RTK can be low.
- Dual frequency still a necessity for reliability

Blue plots shows the horizontal plots at dense urban areas using GPS/QZS/BEIDOU of commercial high-sensitivity receiver.

On the other hand, **red plots** shows the results using only GPS.

The performance difference is clear.

BeiDou

- BeiDou Satellite System (BDS) provides PNT services in the Asia-Pacific corridor
- Current constellation consists of fourteen: including five GEO, five IGSO and four MEO satellites.
- They transmit on B1, B2 and B3 frequencies using QPSK modulation and utilize CDMA

- Current (Phase II) B1 civil signal with 4.092MHz bandwidth centered at 1561.098MHz
- Phase III plan : B1 shifted to GPS-L1 frequency with multiplex binary offset carrier (MBOC 6,1,1/11) modulation.
- BDS should reach its full constellation of 35 satellites by 2020.

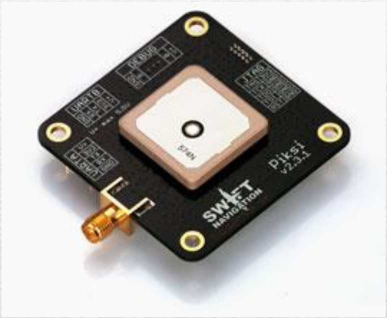
- Focus on performance comparison between GPS-L1, GPS/QZS L1+ BeiDou B1 and GPS L1+L2 in Japan for moving platform in urban environment

http://en.wikipedia.org/wiki/BeiDou_Navigation_Satellite_System

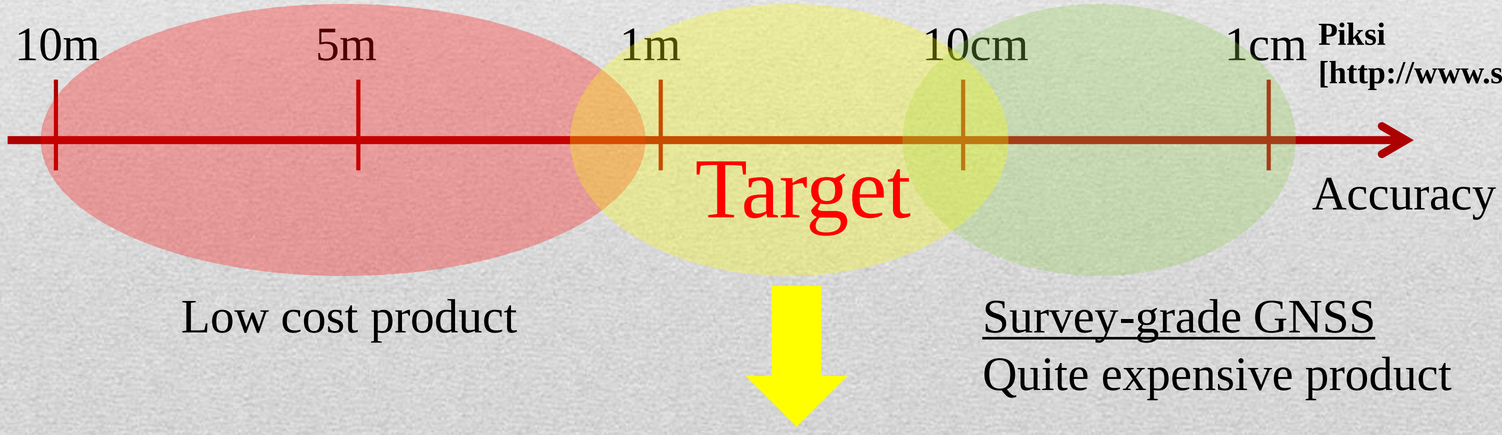
Cost for precision

- Current GNSS-RTK products are expensive – different reasons stable clocks, high-quality antenna, integrated RF front-ends, number of correlators in ASIC, patented algorithms etc.
- Push to support lower cost RTK products for safety applications or UAVs & applications for ubiquity
- Goal is to characterize a low-cost GNSS receiver [u-blox M8] for variety of applications
- When B1 civil signal uses L1 frequency, availability will increase multi-fold in Asia-Pacific

U-blox M8 Receiver [http://diydrones.com/profiles/blogs/ublox-m8-series-gps-glonass-receiver-test]

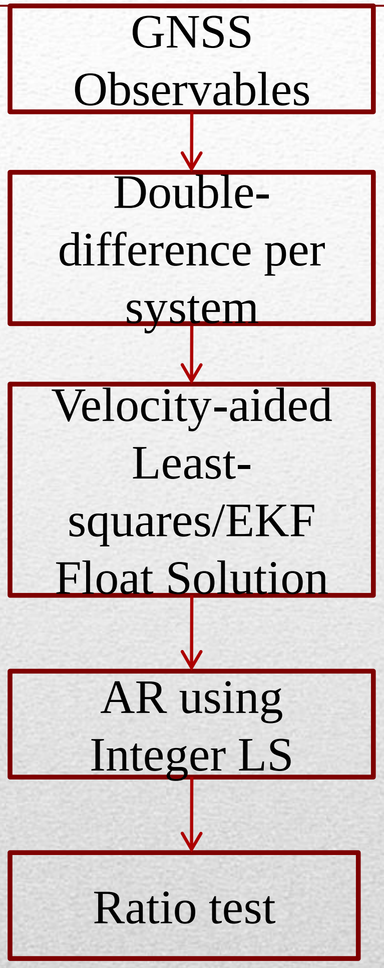


Piksi [http://www.swiftnav.com]



Single epoch RTK-GNSS

- Double-difference Observables
- Atmospheric errors were not considered
- User velocity used when the initial estimates of ambiguities are calculated
- L1 Doppler frequency are used in the velocity estimation.
- Signal quality check and ADOP
- LAMBDA method
- Ratio Test (>3)



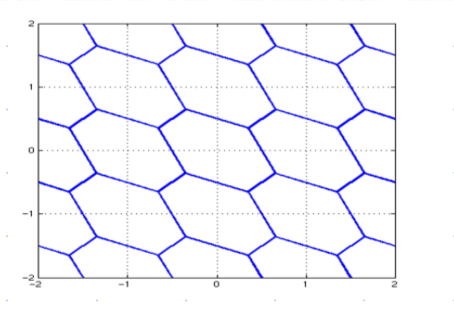
Algorithm

$$E\begin{bmatrix}\phi\\p\end{bmatrix} = \begin{bmatrix}\Lambda & A\\0 & A\end{bmatrix}\begin{bmatrix}a\\b\end{bmatrix}, V\begin{bmatrix}\phi\\p\end{bmatrix} = \begin{bmatrix}Q_{\phi\phi} & 0\\0 & Q_{pp}\end{bmatrix}$$

$$\{\tilde{a},\tilde{b}\} = arg \min_{a\in\mathbb{Z}^n, b\in\mathbb{R}^v}(\|\phi - \Lambda a - Ab\|^2_{Q_{\phi\phi}} + \|p - Ab\|^2_{Q_{pp}})$$

$$\hat{b} = Q_{\hat{b}\hat{b}}A^T Q_{pp}^{-1} p \qquad Q_{\hat{b}\hat{b}} = (A^T Q_{pp}^{-1} A)^{-1}$$

$$\hat{a} = \Lambda^{-1}(\phi - A\hat{b}), Q_{\hat{a}\hat{a}} = \Lambda^{-1}(Q_{\phi\phi} + AQ_{\hat{b}\hat{b}}A^T)\Lambda^{-1}$$



$$\tilde{a} = arg \min_{z\in\mathbb{Z}^n}(\|\hat{a} - z\|^2_{Q_{\hat{a}\hat{a}}})$$

$$\tilde{b} = Q_{\tilde{b}\tilde{b}}A^T[Q_{pp}^{-1}p + Q_{\phi\phi}^{-1}(\phi - \Lambda\tilde{a})]$$

$$Q_{\tilde{b}\tilde{b}} = (A^T(Q_{pp}^{-1} + Q_{\phi\phi}^{-1})A)^{-1} \qquad Q_{\tilde{b}\tilde{b}} \ll Q_{\hat{b}\hat{b}} \text{ if } Q_{\phi\phi} \ll Q_{pp}$$

- respective reference satellites were selected for the BeiDou and GPS systems
- $n_G + 1$ and $n_B + 1$ are the number of GPS/QZS and BDS satellites tracked on L1 and B1 frequencies, a total of $2 * (n_B + n_G)$ DD code and phase observables are available per epoch.
- redundancy in the model was calculated as $(n_G + n_B) - v$
- ILS-based estimators are not only optimal, but have the highest probability of fixing ambiguities among all the integer estimators.
- Empirical fix rate is ratio of the number of passed epochs determined by the ratio test to the total number of observations
- Reliability is equal to the number of correctly fixed epochs divided by the number of passed epochs determined in the ratio test

Experimental Set-up

RECEIVER	**BASE STATION - Trimble NetR9** **ROVER – u-blox EVK-8MT**
ANTENNA	Base station: Trimble Zephyr Geodesic 2 Rover: Novatel 703-GGG
SOFTWARE	Laboratory developed RTK -GNSS engine & RTKLIB 2.4.3

Constellation	Frequency	Code STD (cm)	Phase STD (mm)
GPS	L1	30	3.0
QZS	L1	30	3.0
BDS	B1	30	3.0

Static RTK

- Very short baseline analysis -1m
- Total period: 24 hours
- Different mask angles – 15 & 30 degrees
- Reference station on the rooftop of our building at Etchujima
- Data rate: 1Hz
- Average number of satellites –

  GPS L1 – 8.3 & 6.1

  GPS/QZS L1 and BeiDou B1 – 15.9 & 12

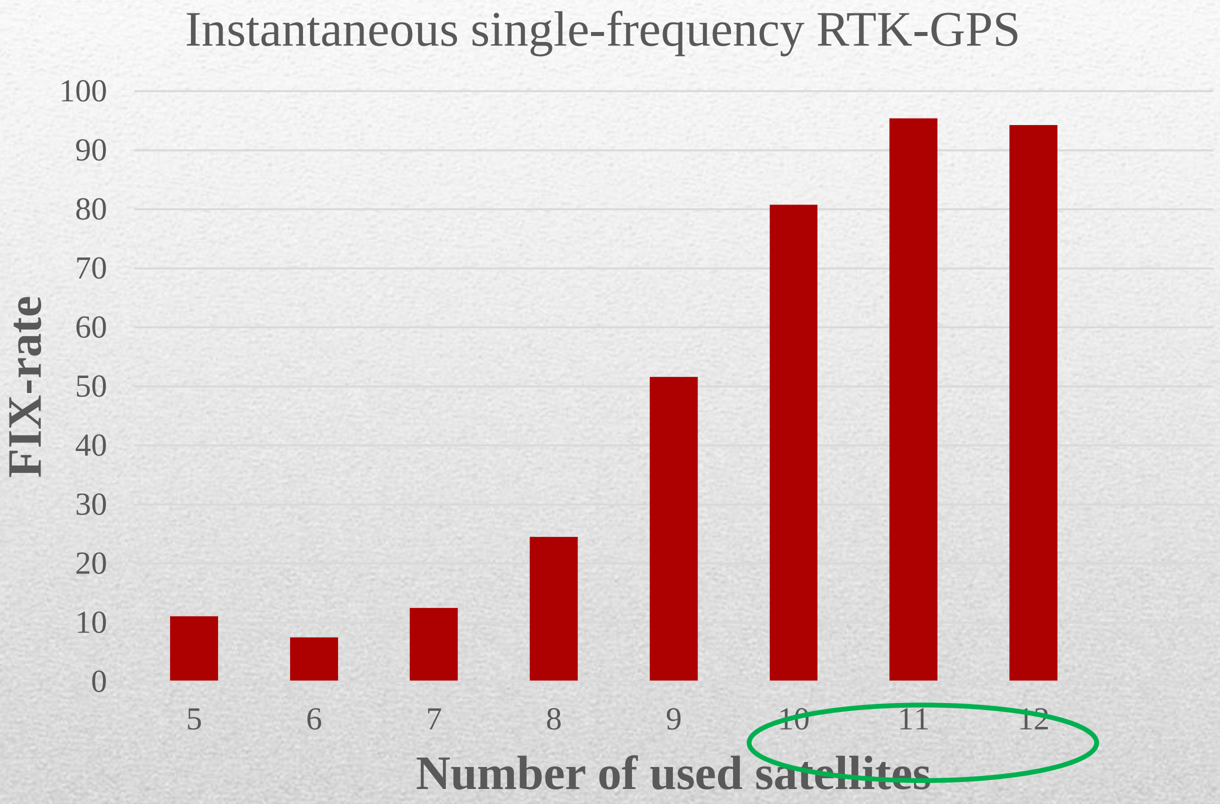
Mask angle = 15 degrees

Combinations	Fix rate (%)	Reliability (%)
GPS	52.53	98.53
GPS+QZS	65.78	99.30
GPS+BDS	99.82	100
GPS/QZS/BDS	99.85	100
GPS (L1+L2)	97.88	100

Mask angle = 30 degrees

Combinations	Fix rate (%)	Reliability (%)
GPS	18.59	91.72
GPS+QZS	28.46	95.35
GPS+BDS	90.85	99.87
GPS/QZS/BDS	92.30	99.90
GPS (L1+L2)	70.76	100

FIX rate and number of used satellites



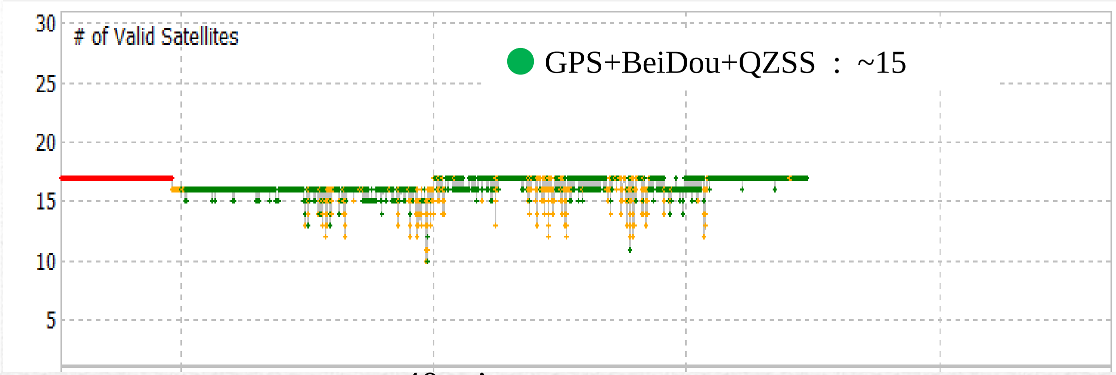
Without any kinds of smoothing technique, single-frequency RTK requires more than 10 satellites to achieve good Fix-rate.

Experiment 1

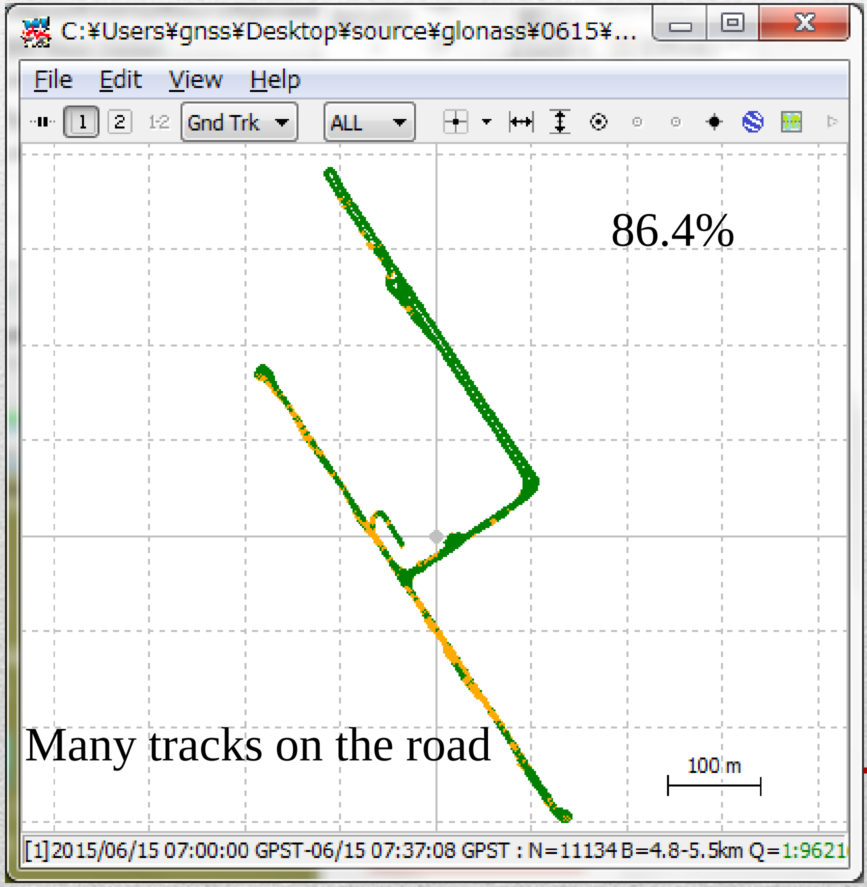
- Automobile testing near ferry terminal
- Urban environment with surrounding low-rise buildings
- Reference station on rooftop of building in Etchujima campus
- Mask angle – 15 degrees
- Test duration - approximately 40 min.

Results

RTKLIB Ratio > 2.5	Instantaneous Fix rate (%)
GPS	35.1%
GPS/QZS	35.1%
GPS/QZS/BEI	86.4%



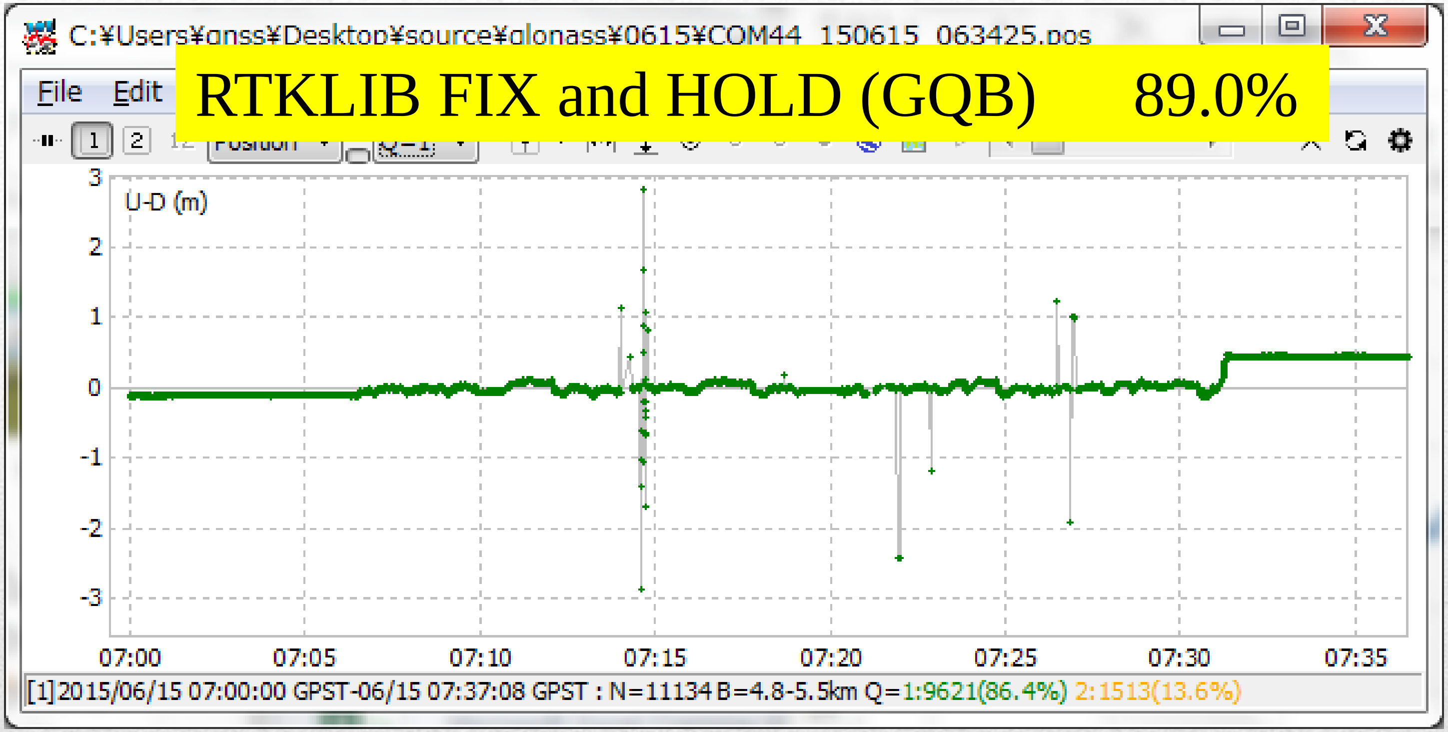
40 minutes

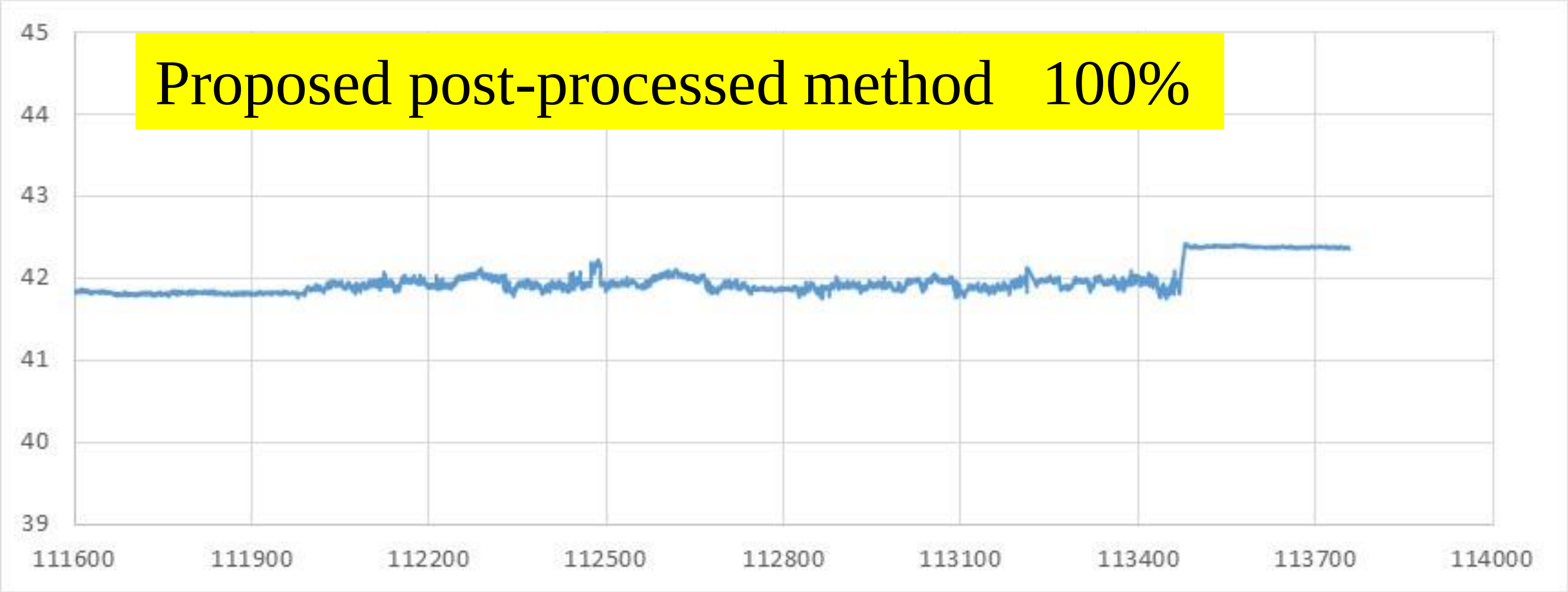


The elevation of QZS was not high (about 30-40 degrees)

RTKLIB FIX and HOLD (GQB) 89.0%
Proposed post-processed method 100%

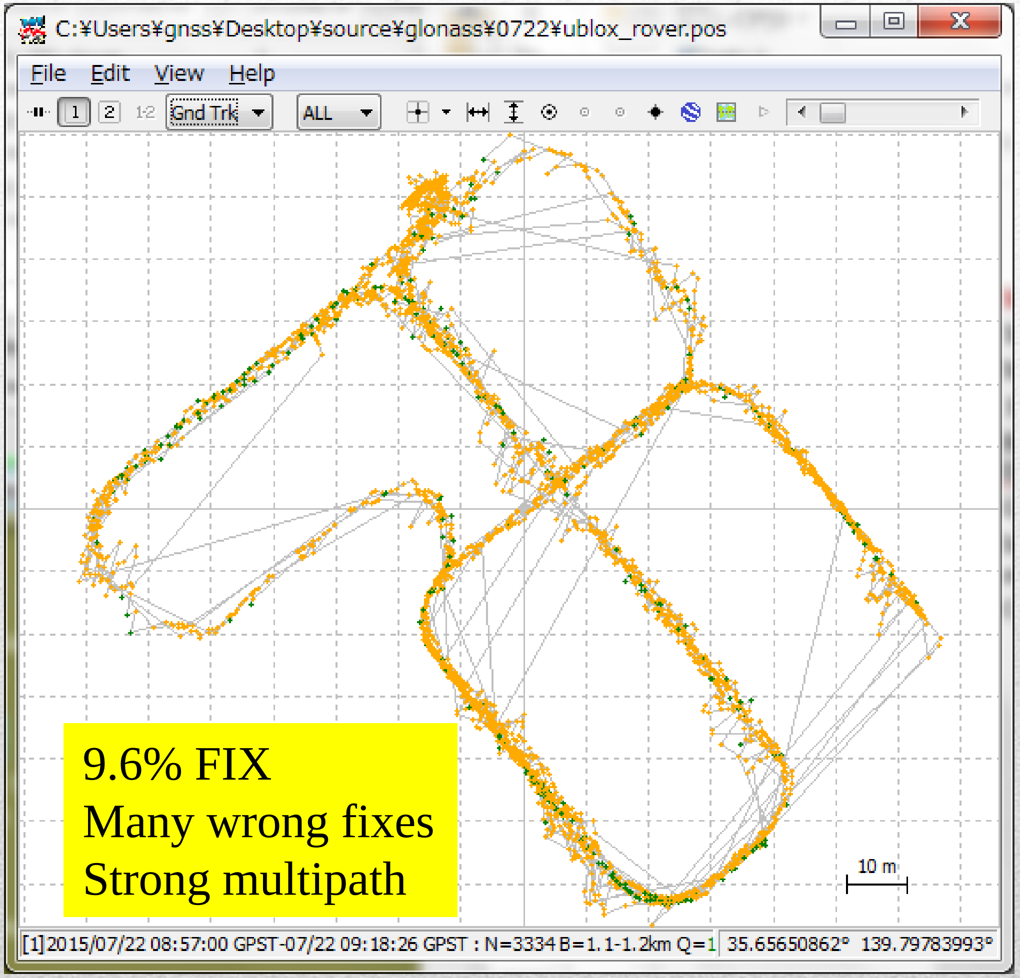
Height Results

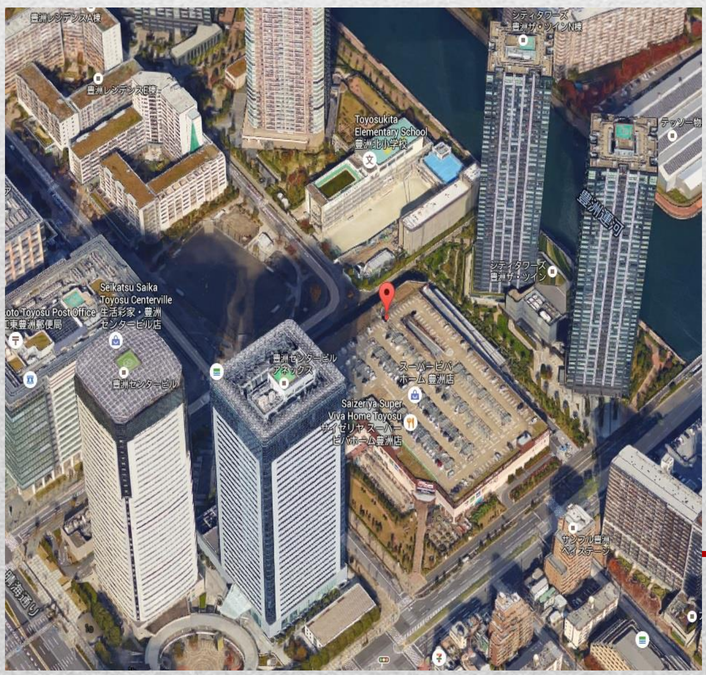




Experiment 2

- Multipath rich urban environment in a parking lot
- Total period : ~25 min
- Mask angles – 15 degrees
- Frequency: 5Hz
- Reference station on the rooftop of our building at Etchujima
- GPS/QZS L1 and BeiDou B1 – ~12
- Instantaneous fix rate around 9.6% despite good availability (many wrong fixes)
- Cycle-slips for most of available satellites





Approach & Results

Ambiguity coasting

Instantaneous AR using Integer LS

Monitor cycle-slips for SATS

↓

VDOPmin to choose best estimates for ambiguities

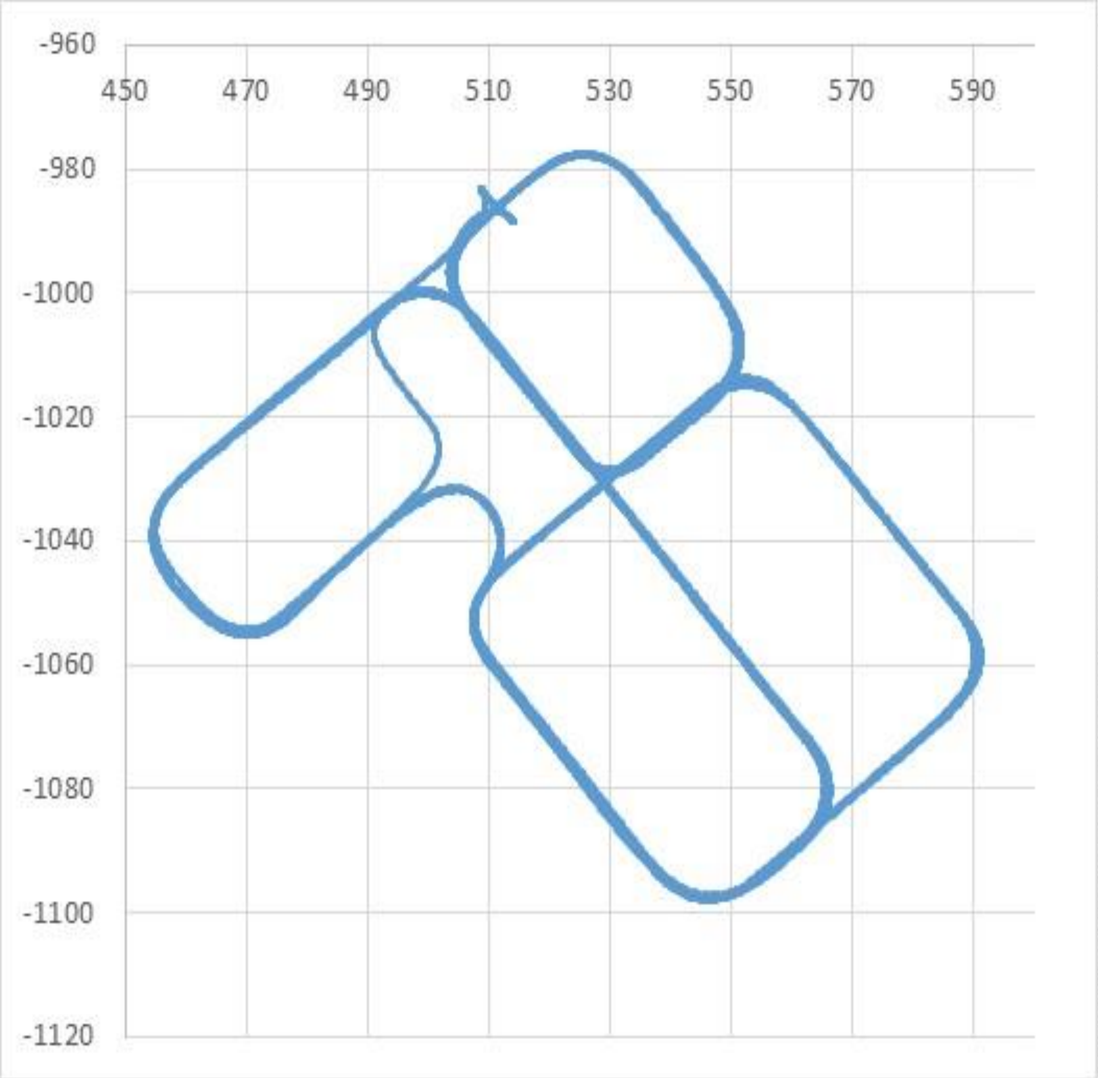
↓

Choose reference satellites

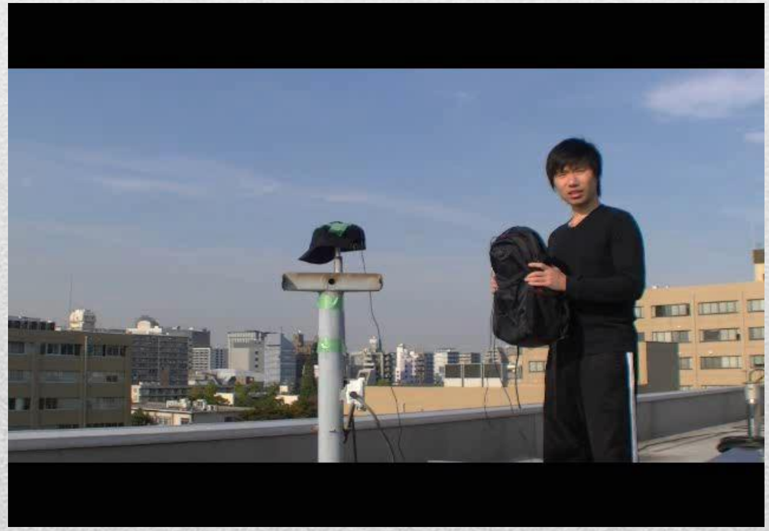
↓

Post-process with hold ambiguities

- 100% position fixes



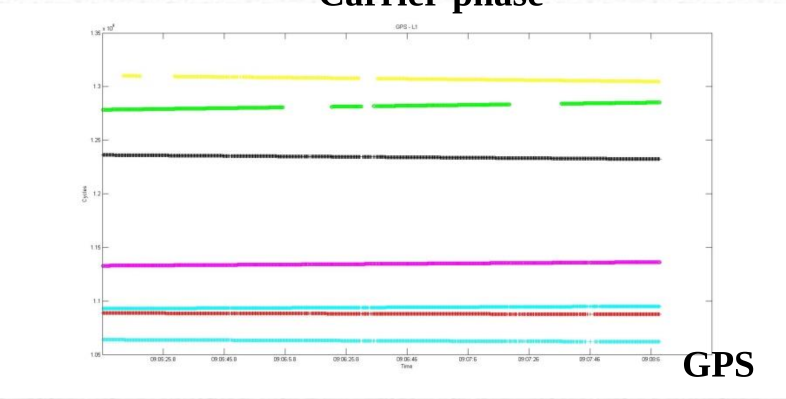
Experiment 3



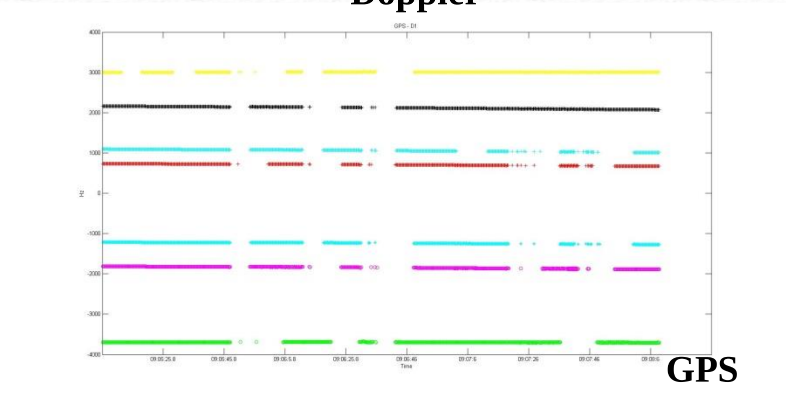
- Sprinting RTK analysis
- Antenna & receiver worn in a backpack on runner’s shoulders
- Base-station antenna placed in proximity
- Single mask angle – 15 degrees
- Two simulations show cycle-slips
- Approximately 10 min with 5Hz rate

Cycle-slips

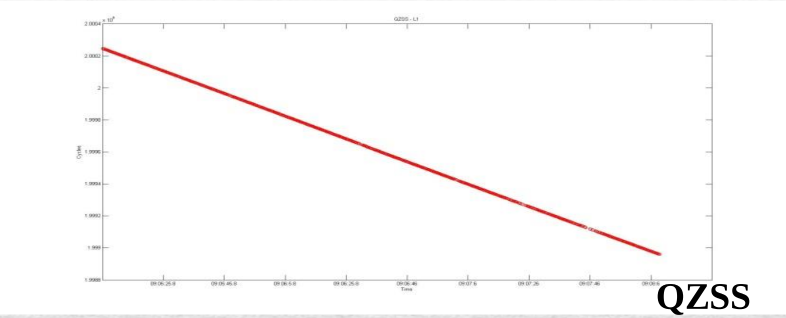
Carrier-phase | **Doppler**



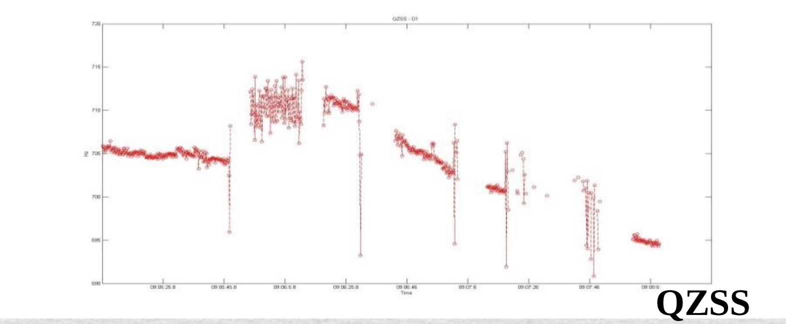
GPS



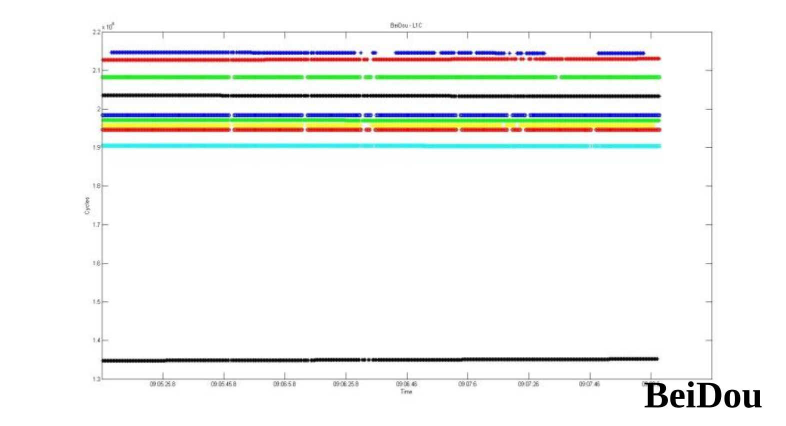
GPS



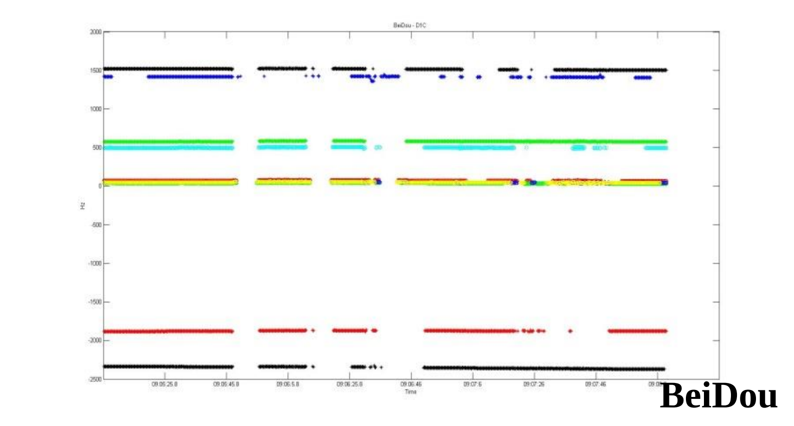
QZSS



QZSS



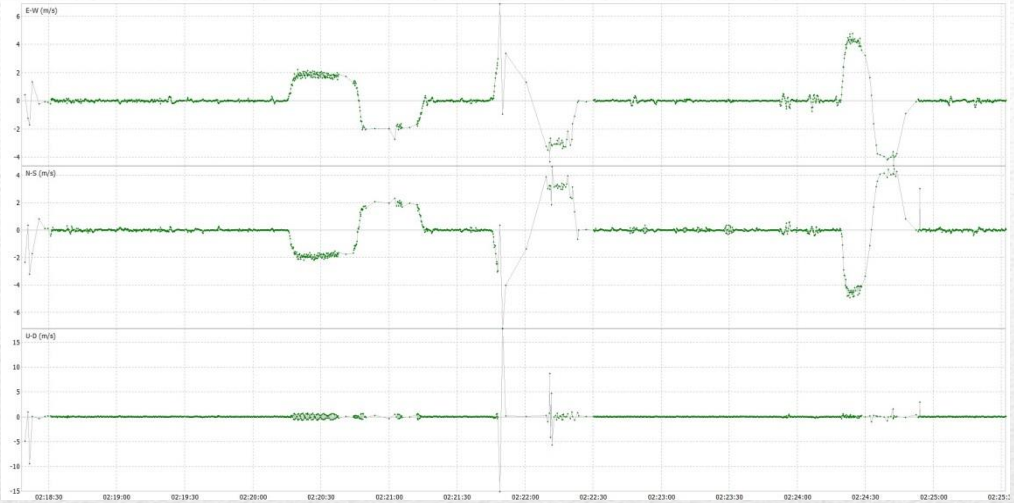
BeiDou



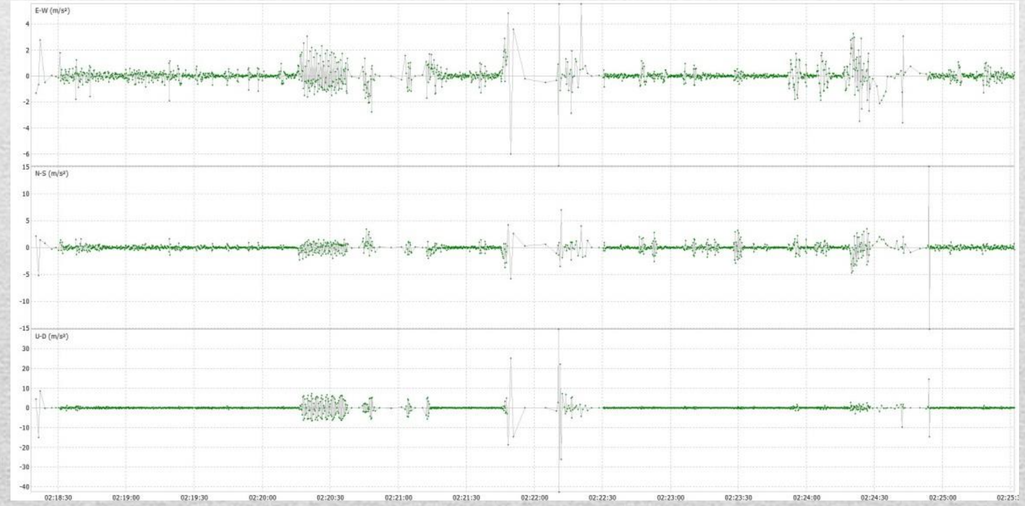
BeiDou

Results

Velocity



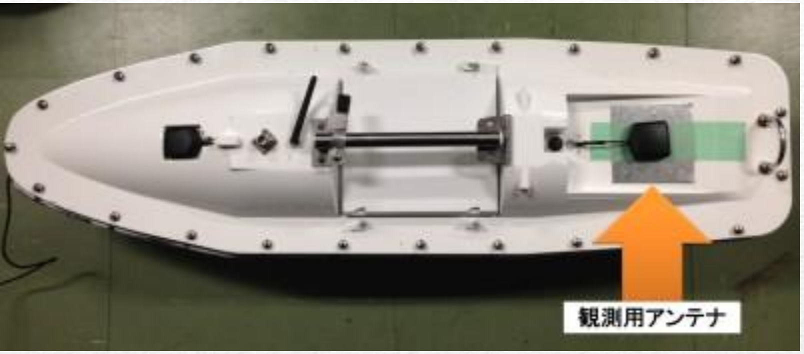
Acceleration

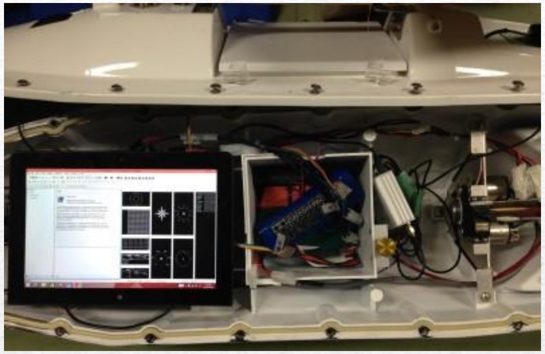


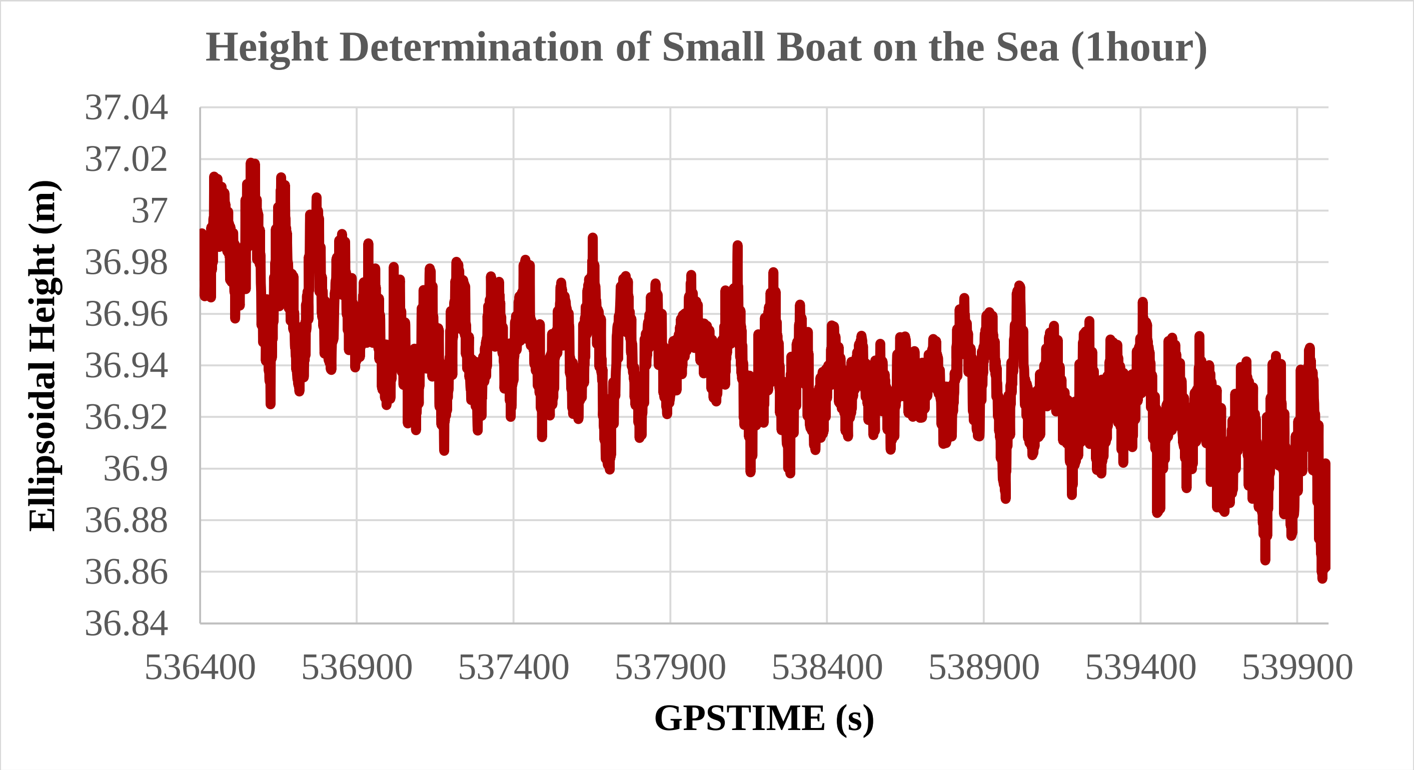
Combinations	Fix rate (%)	Reliability (%)
GPS+QZS+BDS	77.9	100

- Doppler estimates and cycle-slips choppy data
- Reason -Acceleration in vertical direction can be 3g or 4g, low-cost TCXO is not stable with high vibration
- Receiver cannot handle acceleration & jerk of that magnitude

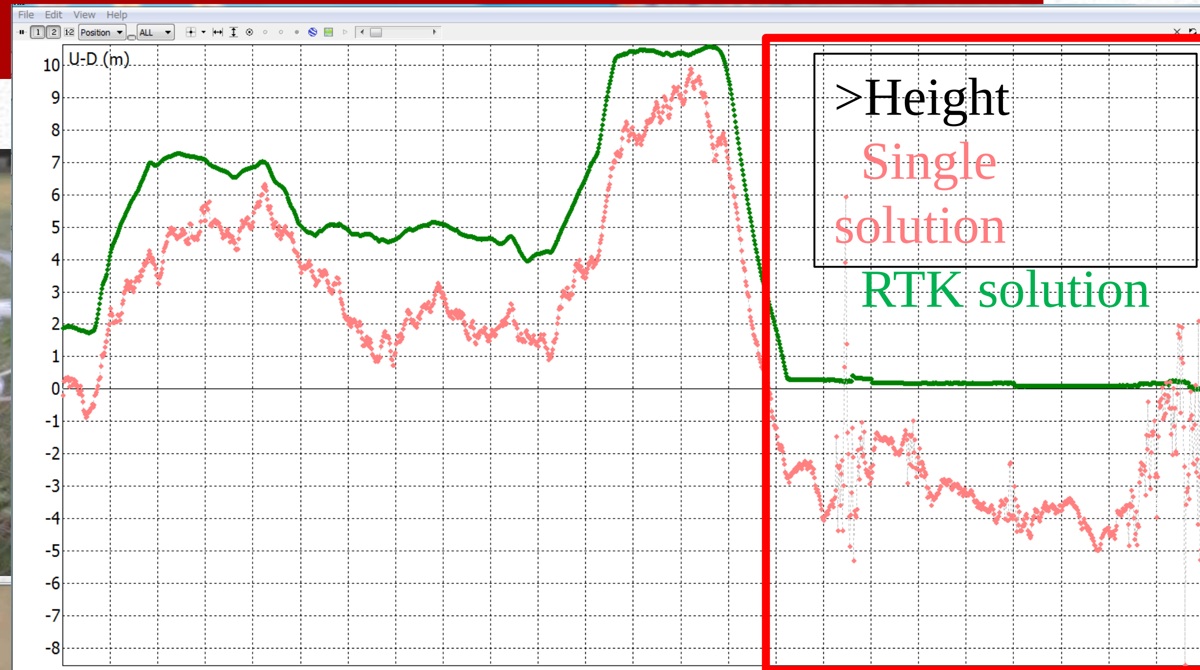
Altitude determination for boat

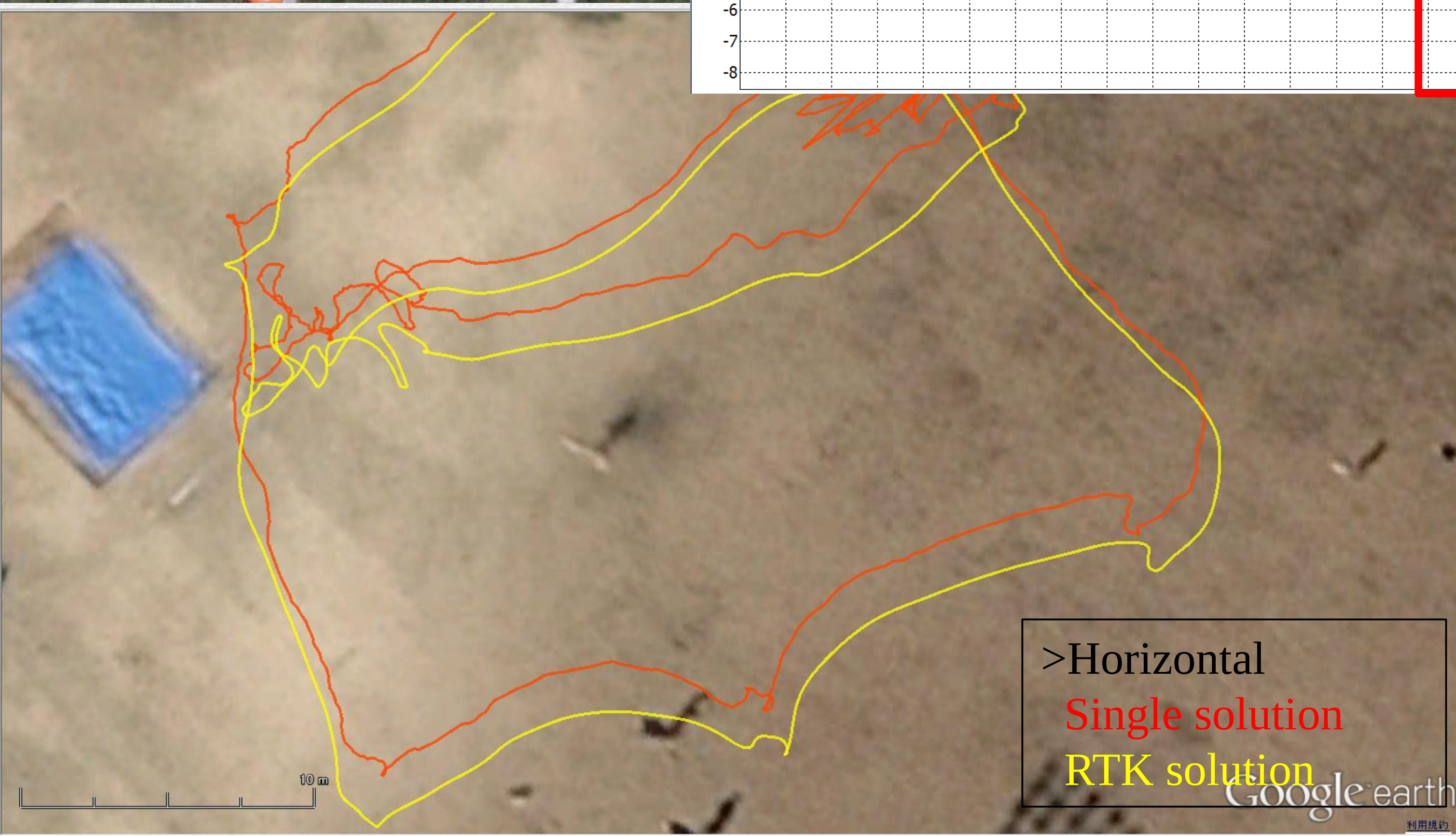






RTK for UAV


U-D (m)
>Height
Single solution
RTK solution


>Horizontal
Single solution
RTK solution
10 m
Google earth

Summary

- By adding QZS, BeiDou, or QZS/BeiDou to GPS only, fix rate and reliability of RTK improved significantly under various conditions.

- First reason : high satellite availability improves ambiguity resolution.

even under open sky conditions more than 10-11 satellites are generally required.

- Second reason: good selectability;

set a high cut off angle if we have redundancies to result in good quality selection.

- Avoiding the multipath reflections is quite important too.
- Low-cost TCXO seems to be not stable with high vibration and acceleration etc.

Proposed post-processed RTK software will be released in this month.
please check the following website later.
http://www.denshi.e.kaiyodai.ac.jp/jp/

Thank you for your attention !