Single-Frequency Multi-GNSS RTK Positioning for Moving Platform

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Agenda

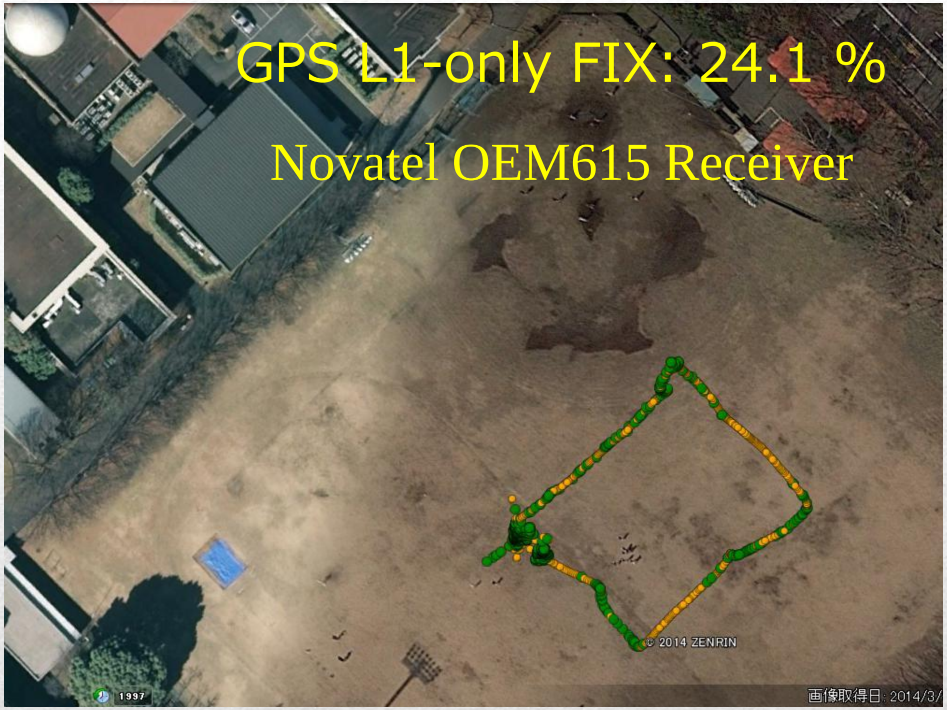
- Motivation and Background
- Single-epoch multi-GNSS RTK
- Short baseline analysis
  -Experiment and Results
- 5KM baseline analysis
  -Experiment and Results
- Crane motion
  -Experiment and Results
- Automobile test
  -Experiment and Results
- Summary
- Future Direction

Motivation & Background

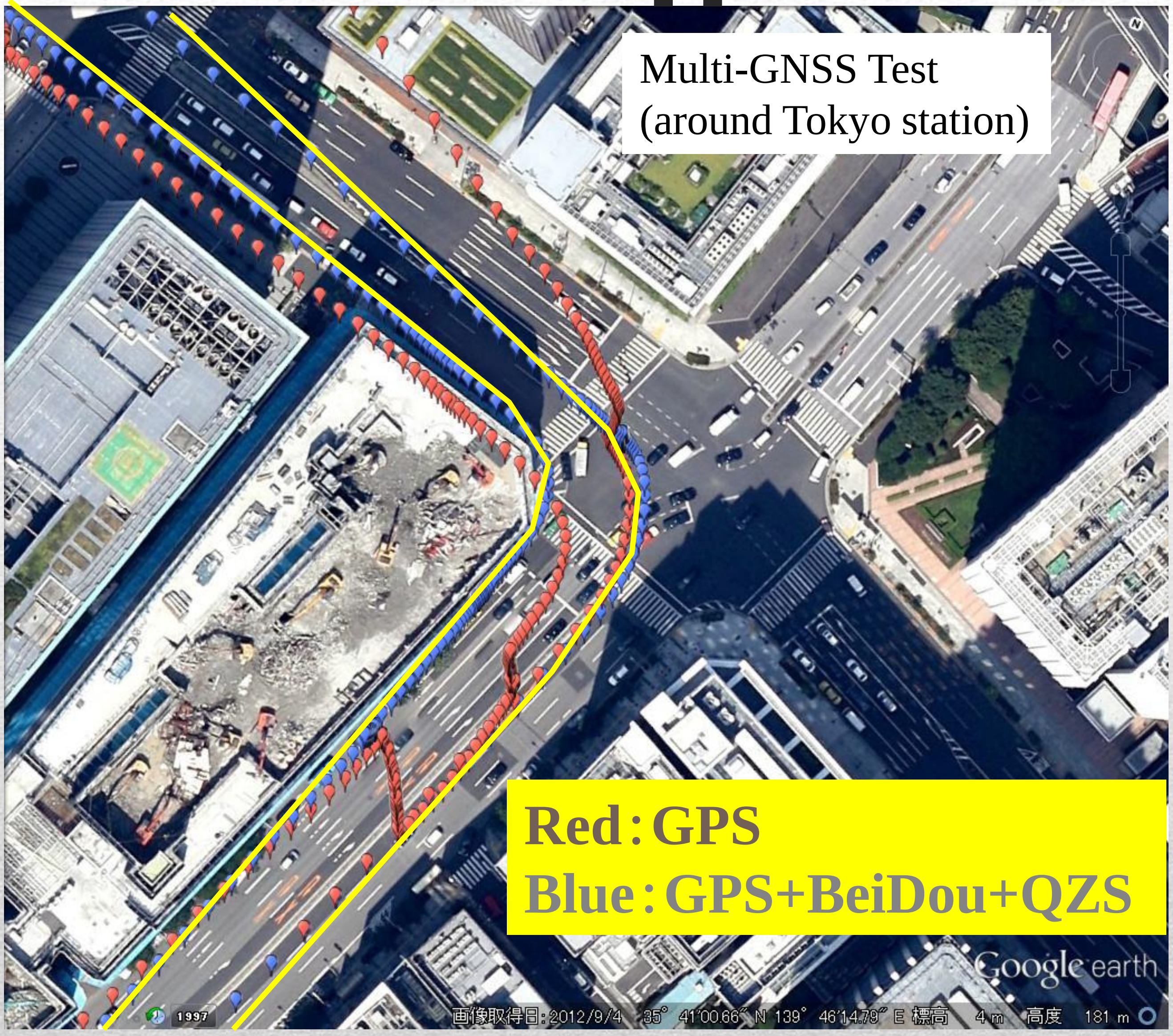
- Possible to achieve high precision positioning with RTK-GNSS
- Prospective accuracy for safety apps like lane recognition is to be under 1m with continuous positioning

Low-cost precise position apps:

- UAV : Centimeter-level accuracy allows it to be used for precise map generation.
- Crane motion : Cost of precise verification of a large crane remains excessive.



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.

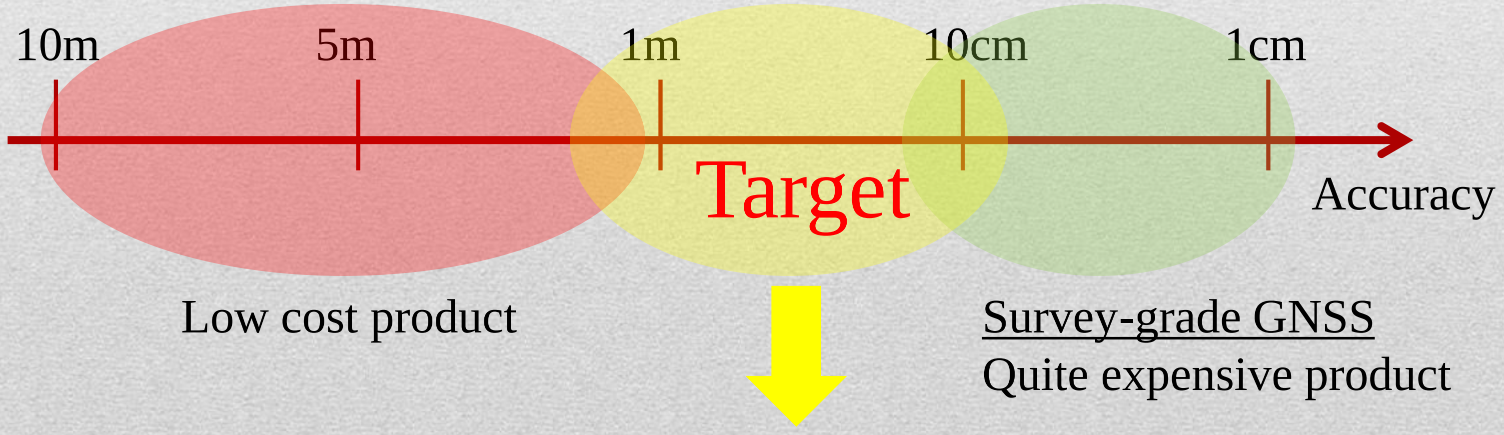
- Focus on performance comparison between GPS-L1, GPS/QZS L1+ BeiDou B1 and GPS L1+L2 in Japan for moving platform in urban environment

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

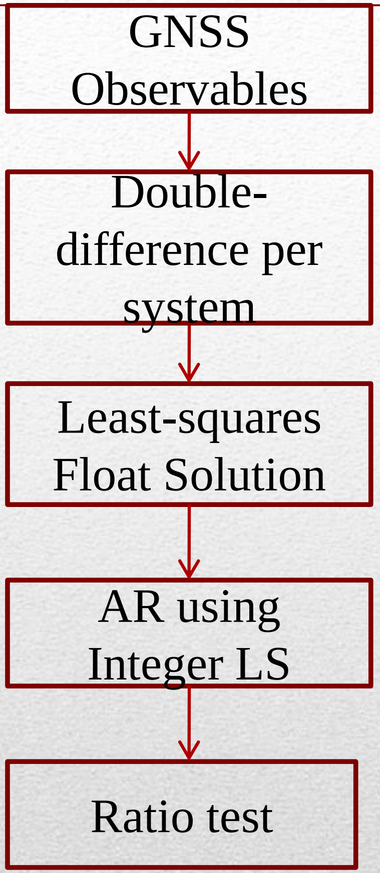
Cost for precision

- 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
- When B1 civil signal uses L1 frequency, availability will increase multi-fold in Asia-Pacific

Piksi http://www.swiftnav.com]



Single epoch RTK-GNSS



- Double-differenced observations in each satellite system
- Signal quality check and ADOP
- LAMBDA method
- Ratio Test (>3)

It is expected that the multi-GNSS RTK will be improved by using many satellites

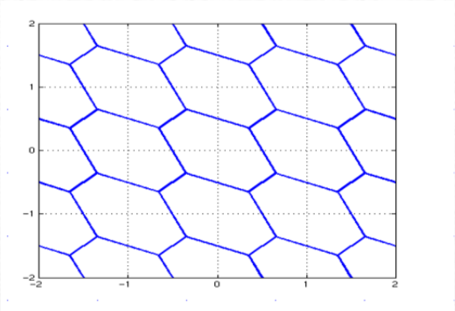
Algorithm

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

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

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

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



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

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

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

- 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 AND ROVER)	**Trimble NetR9**
ANTENNA	Base station: Trimble Zephyr Geodesic 2 Rover: Novatel 703-GGG
SOFTWARE	Laboratory developed RTK -GNSS engine

Constellation	Frequency	Code STD (cm)	Phase STD (mm)
GPS	L1	35	3.5
QZS	L1	35	3.5
BDS	B1	35	3.5

Experiment 1 -1m baseline

- 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

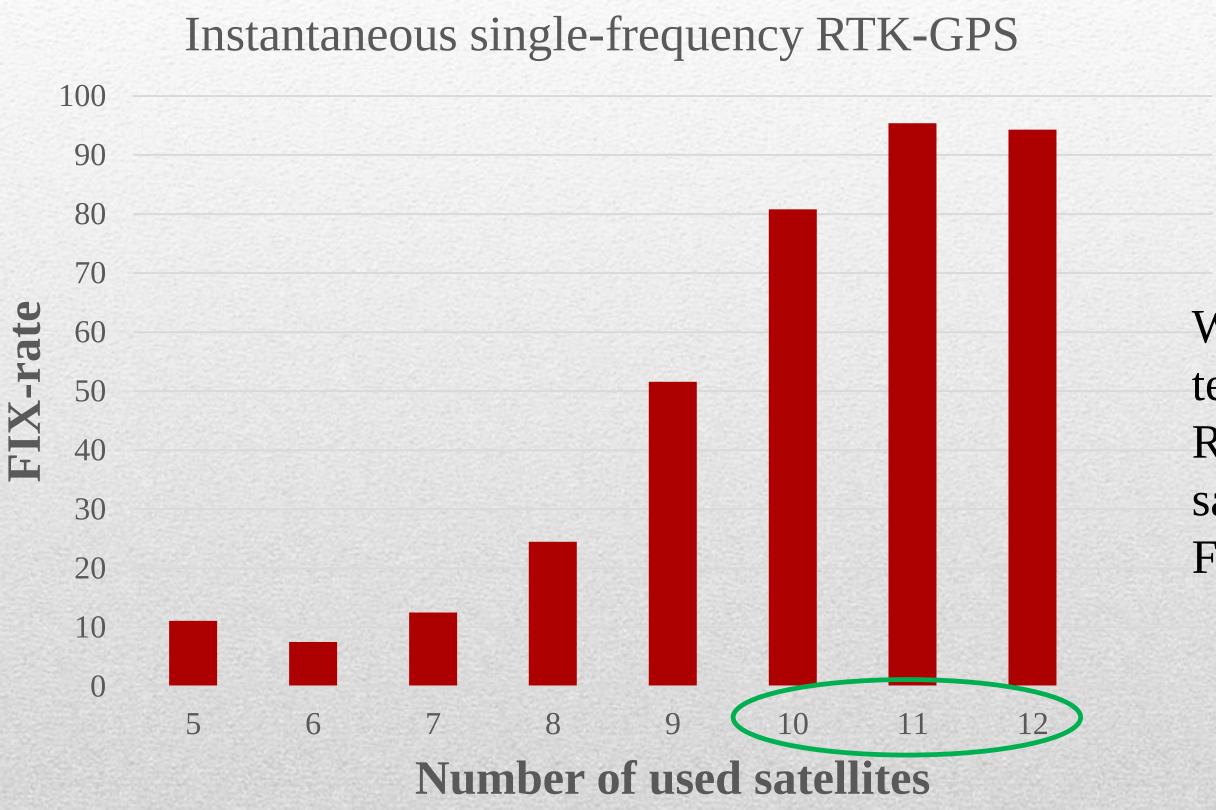
Mask angle = 15 degrees

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 2 -5KM baseline

- 5KM baseline analysis
- Total period : 18 hours
- Different mask angles – 15 & 30 degrees
- Frequency: 1Hz
- Reference station on the rooftop of our building at Etchujima
- QZSS ignored due to unstable and inconsistent data
- Average number of satellites used-

  GPS L1 – 7.9 & 6.1

  GPS/QZS L1 and BeiDou B1 – 15.8 & 11.7

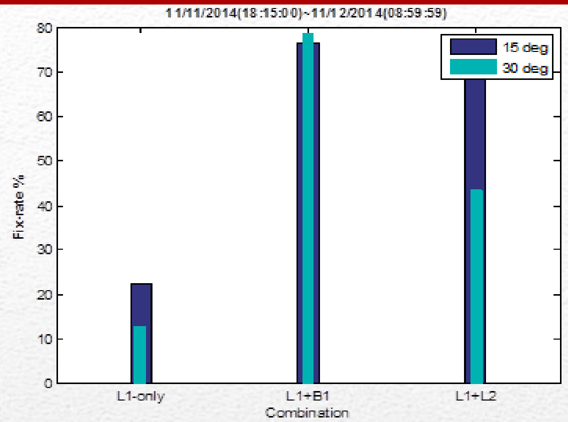
Mask angle = 15 degrees

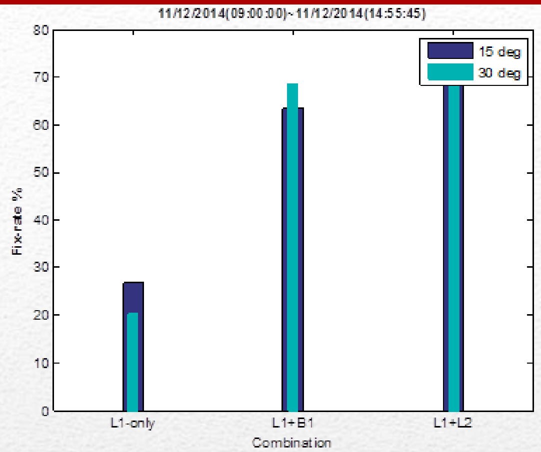
Combinations	Fix rate (%)	Reliability (%)
GPS	27.2	95.71
GPS+BDS	73.9	99.98
GPS (L1+L2)	79.7	100

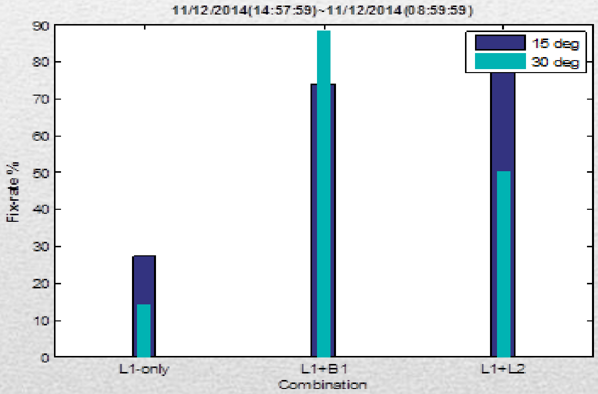
Mask angle = 30 degrees

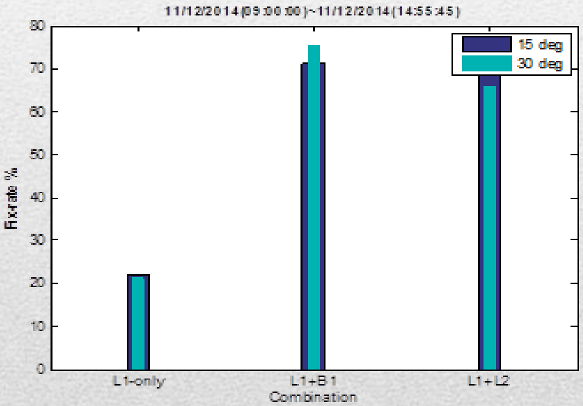
Combinations	Fix rate (%)	Reliability (%)
GPS	14.0	92.73
GPS+BDS	88.2	99.90
GPS (L1+L2)	50.1	100

Satellite availability









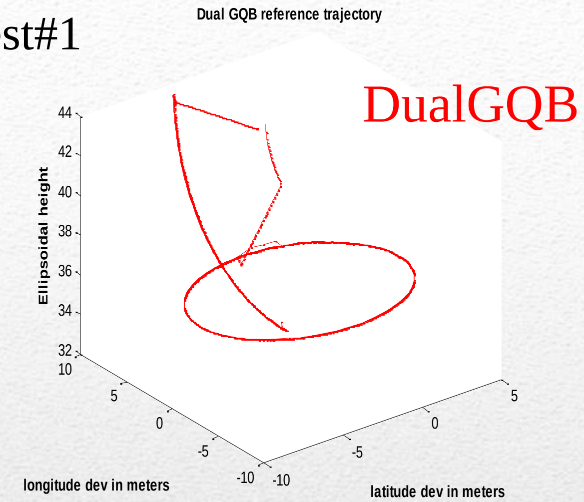
- L1+B1 combination provides best availability for both mask angles.
- For successful fix rate, L1+B1's performance comparable to L1+L2's for 15degrees mask angle and betters for 30degree mask angle .
- L1+B1 has better reliability owing to this consistency.
- A mask angle 30 deg similar to may be necessary to keep multipath effects in check.

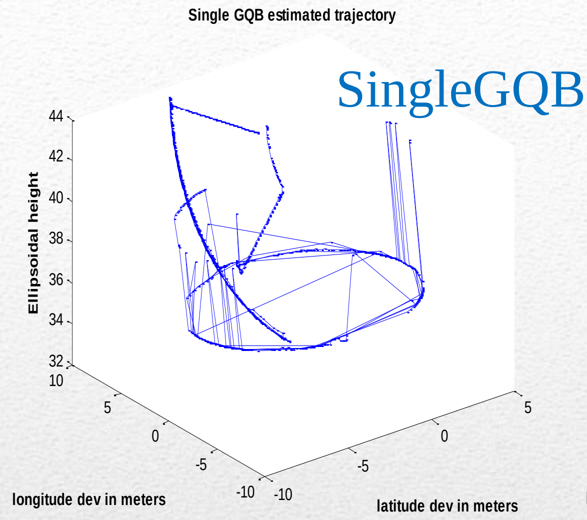
Experiment 3

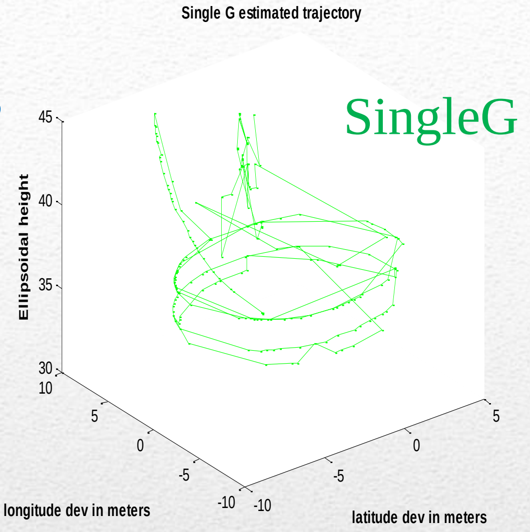
- Crane motion analysis
- Moving reference station - Antenna & receiver at higher elevation on the crane
- Rover antenna placed on the blue side-post shown
- Single mask angle – 35 degrees
- Two tests carried out – **closer & away from wall**
- Each experiment lasted approximately 30 min.

Estimated Trajectories

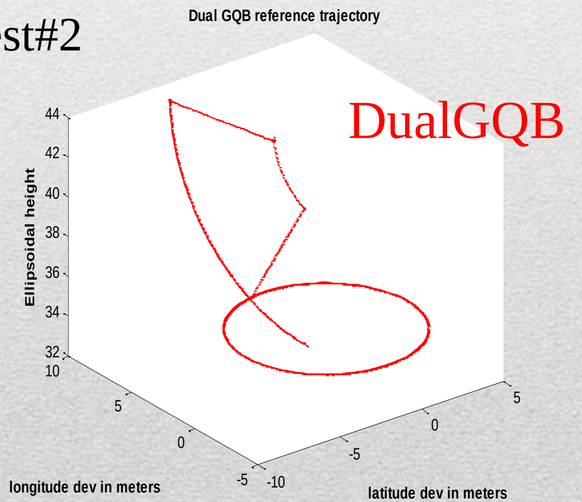
Test#1

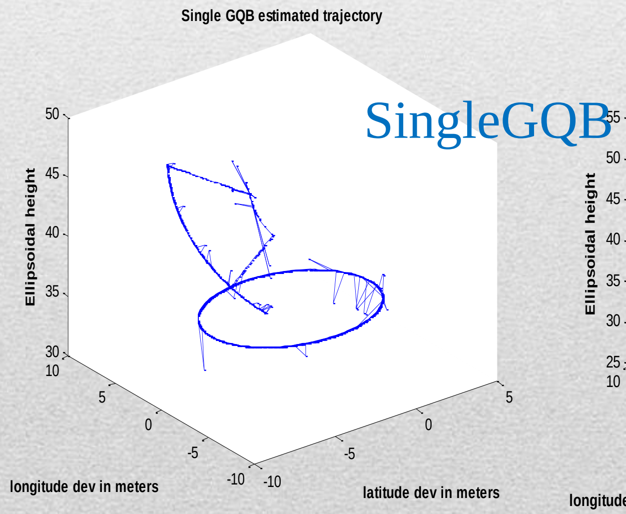


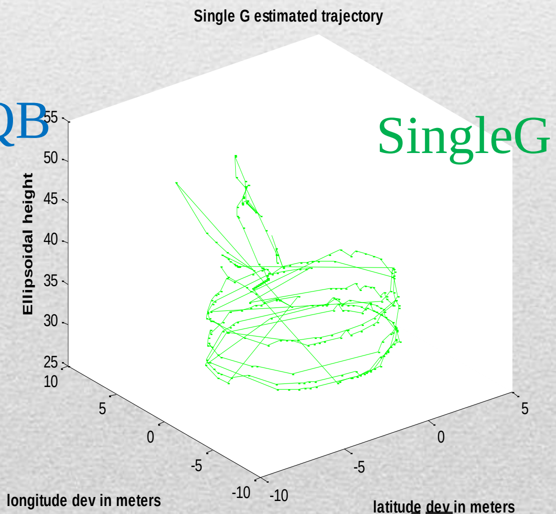




Test#2







Results

Test #1= Away from wall (over 30m)

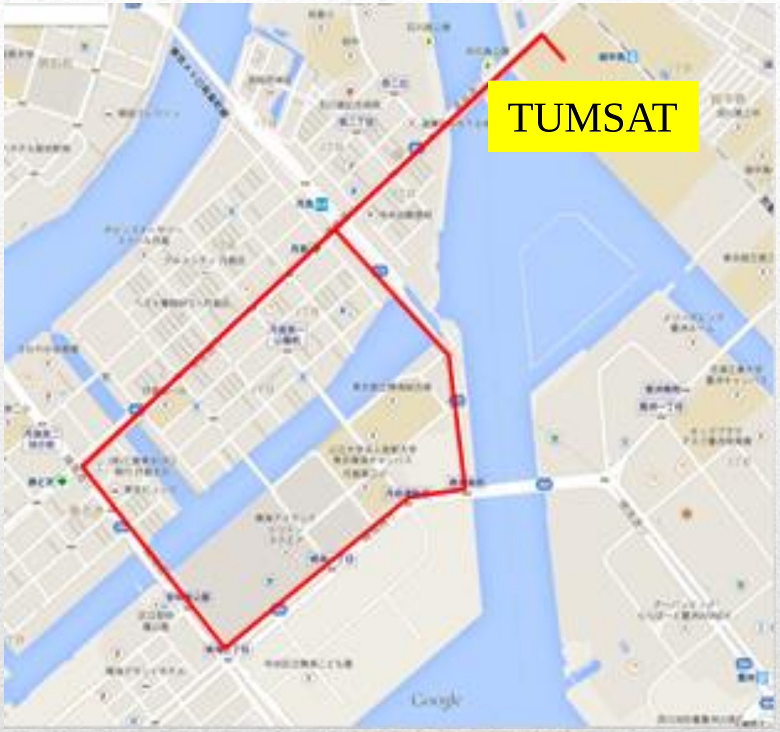
Combinations	Fix rate (%)	Reliability (%)
GPS	7.65	50.08
GPS+QZS	31.78	96.96
GPS+QZS+BDS	86.95	99.41
GPS+QZS+BDS (dual-frequency)	99.85	100

Test#2= Closer to wall (approx. 15m)

Combinations	Fix rate (%)	Reliability (%)
GPS	14.47	0.25
GPS+QZS	9.16	72.76
GPS+QZS+BDS	56.17	98.28
GPS+QZS+BDS (dual-frequency)	98.93	100

- Reason we chose "moving reference station" was so it would have open sky view.
- True reference positions of the crane motion unknown, hence dual frequency derived results used as a reference
- If we set the mask angle below 30 degrees, the fix rate and reliability decreased dramatically for all combinations.
- Explained by vulnerability of single frequency RTK to small/medium multipath environment
- The performance difference between test1 and test2 evident from estimated trajectories
- The reliability of the only GPS case very poor at almost 0%
- In test1, single GQB fares almost as well as dual GQB.
- In test2, single GQB combination does not fare as well but dual GQB presents an almost perfect result.

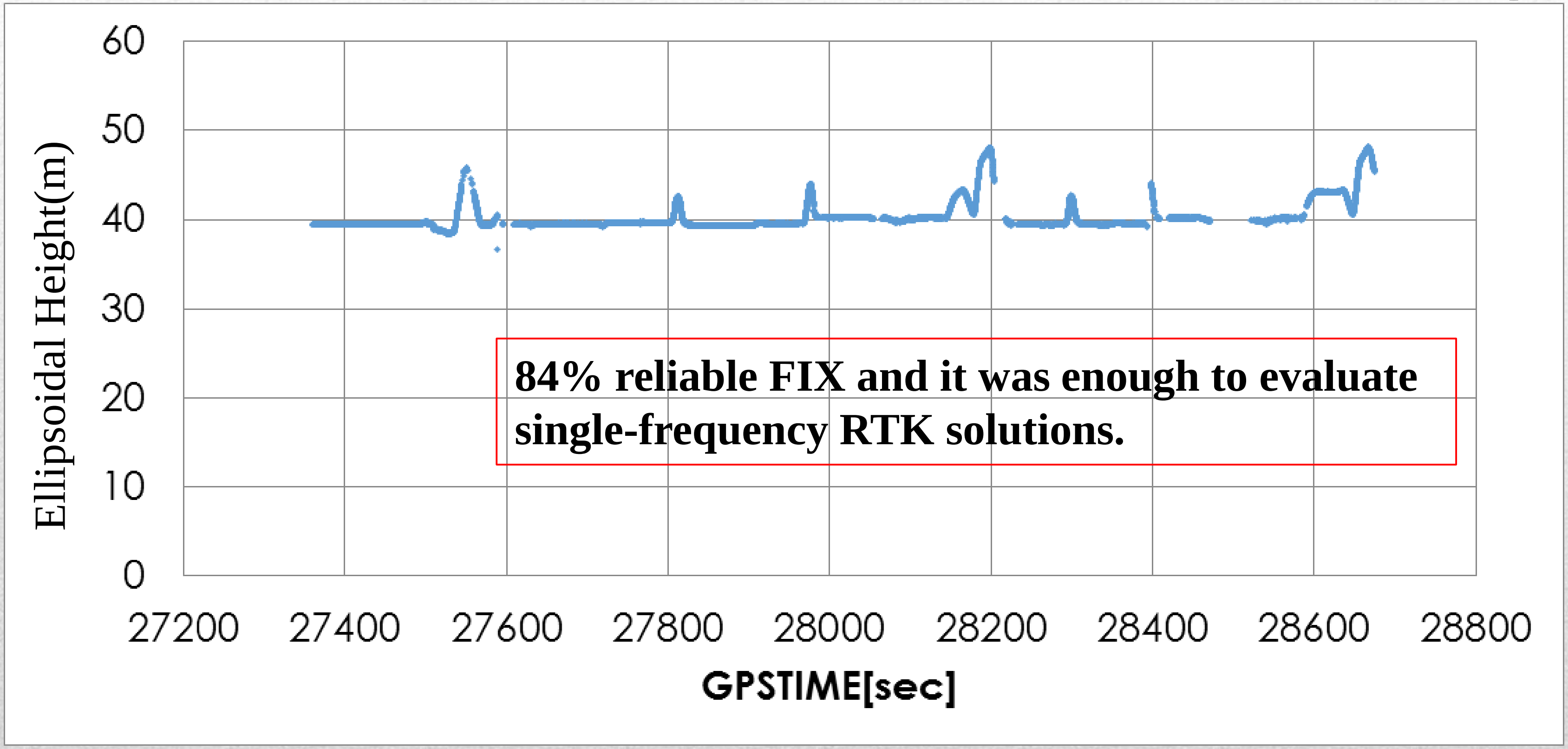
Experiment 4



- Automobile testing near university campus
- Urban environment with surrounding buildings
- Reference station on rooftop of building in Etchujima campus
- QZS was not available due to low elevation angle.
- Mask angle – 15 degrees
- Test duration - approximately 25 min.

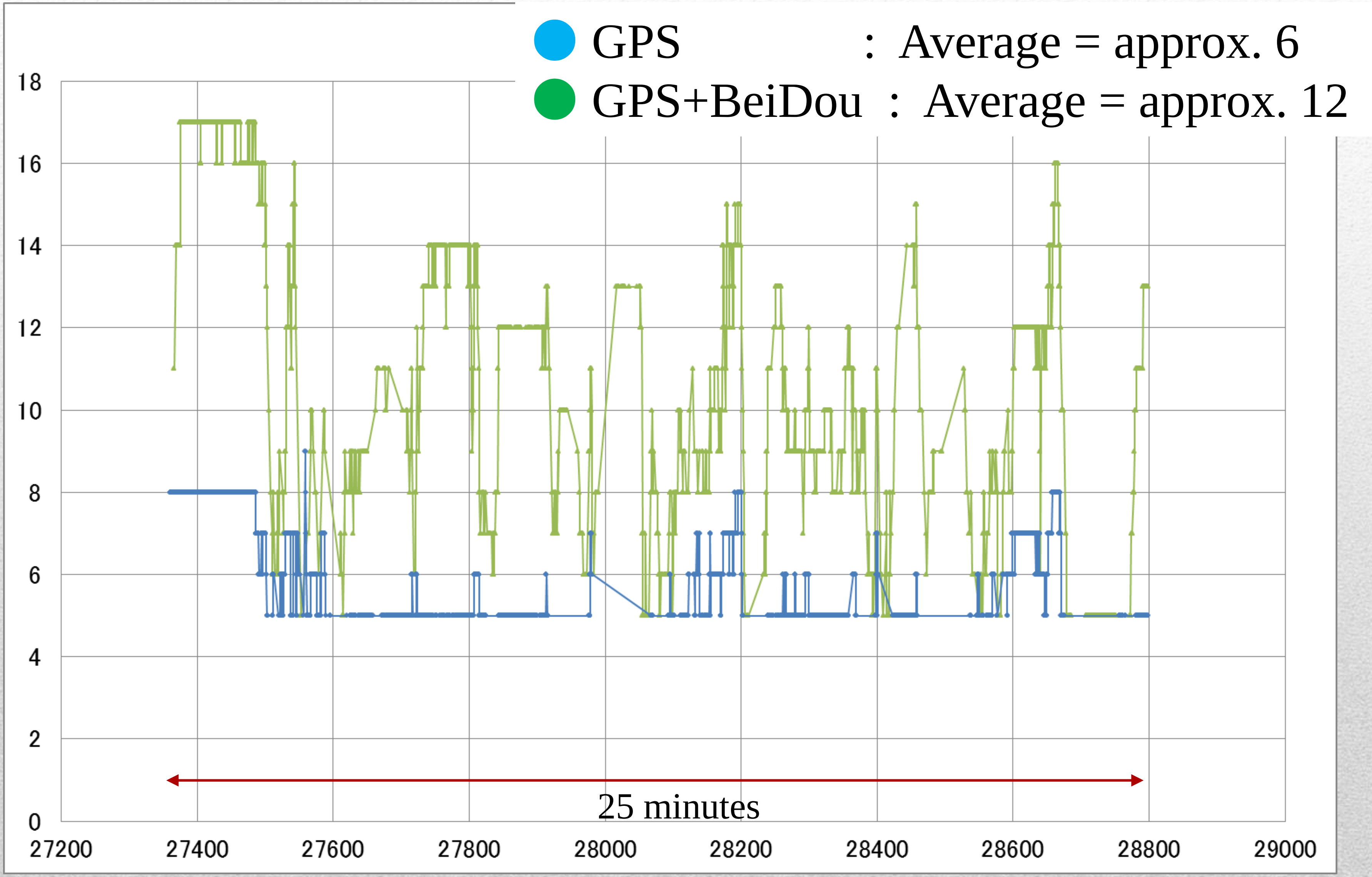
Reference Positions by Multi-GNSS RTK

GPS+QZS+GLONASS+BEIDOU dual-frequency



Number of used satellites

GPS and GPS+BEIDOU

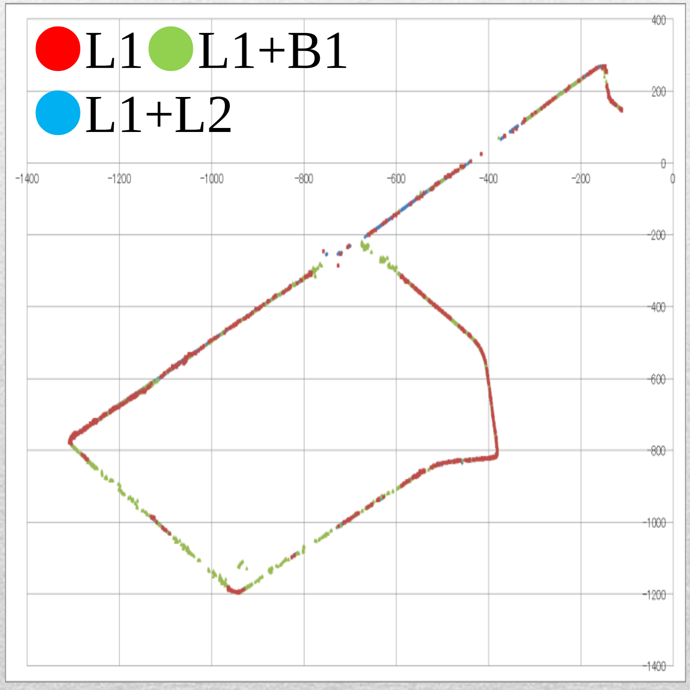


Results

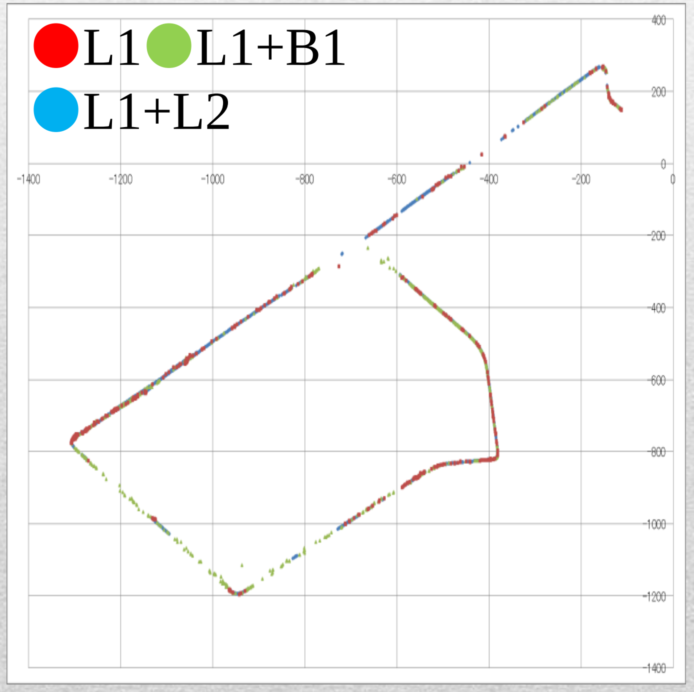
Ratio 2	Fix rate (%)	Reliability (%)	HDOP
GPS	13	27.8	4.3
GPS+BDS	28.2	85.9	1.3
GPS(L1/L2)	44.5	99.8	4.1

Ratio 3	Fix rate (%)	Reliability (%)	HDOP
GPS	5.5	28.7	4.3
GPS+BDS	15.1	91.9	1.1
GPS(L1/L2)	35.2	100	3.9

Ratio test threshold = 2



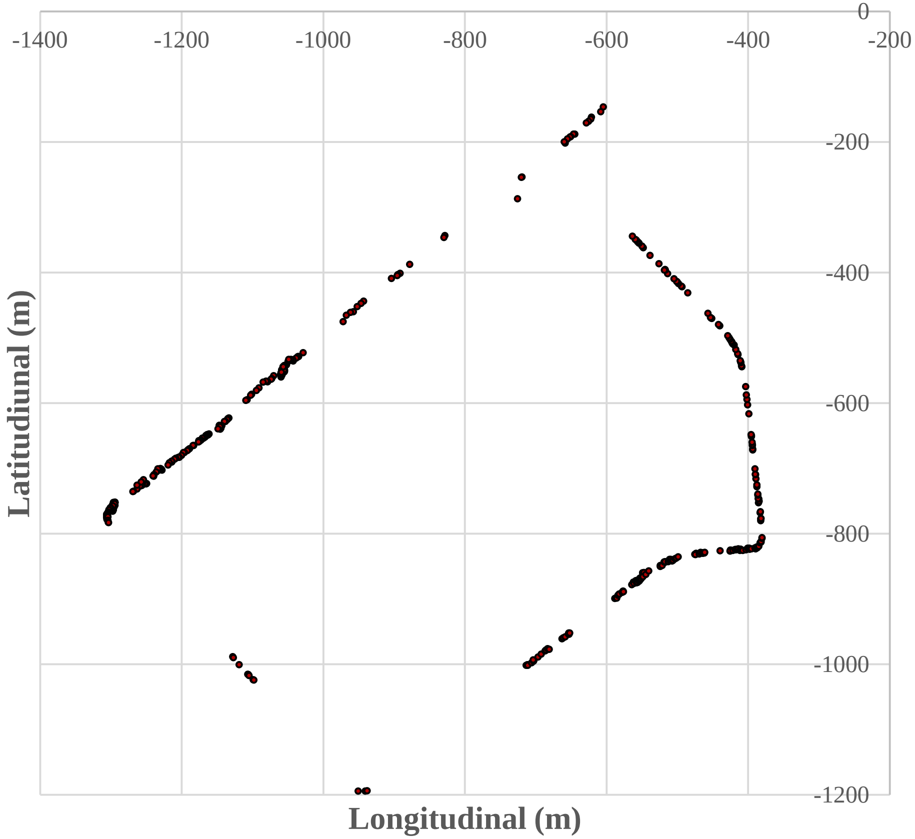
Ratio test threshold = 3



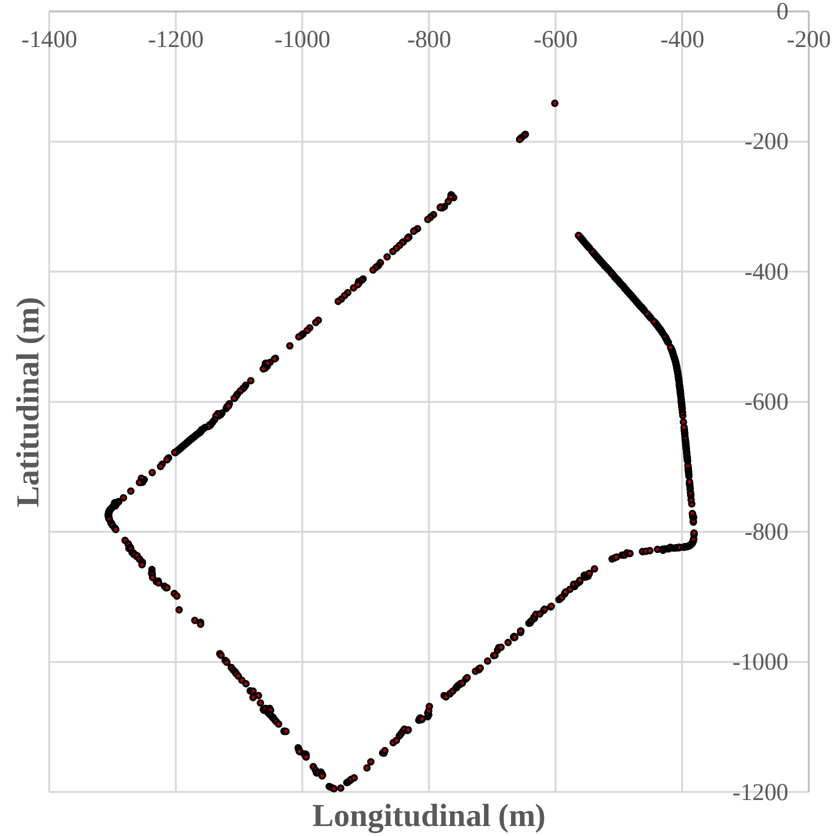
Reliability means the percentage within 50cm of horizontal errors

Comparisons

- GPS and GPS/BeiDou Ratio>2 1 Round-



GPS (L1)



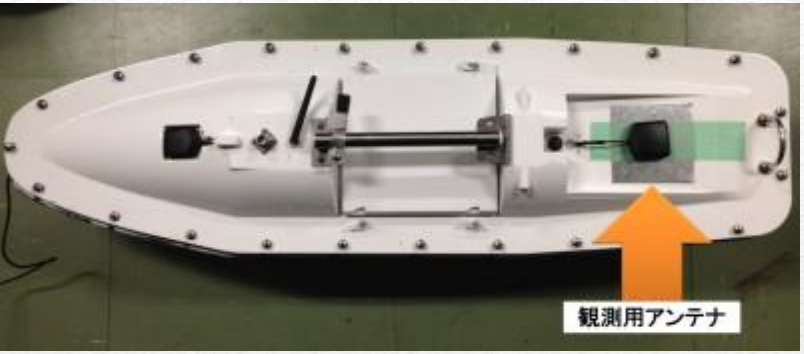
GPS+BeiDou (L1/B1)

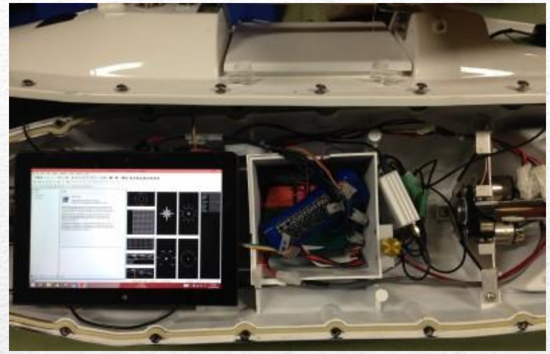
Discussion

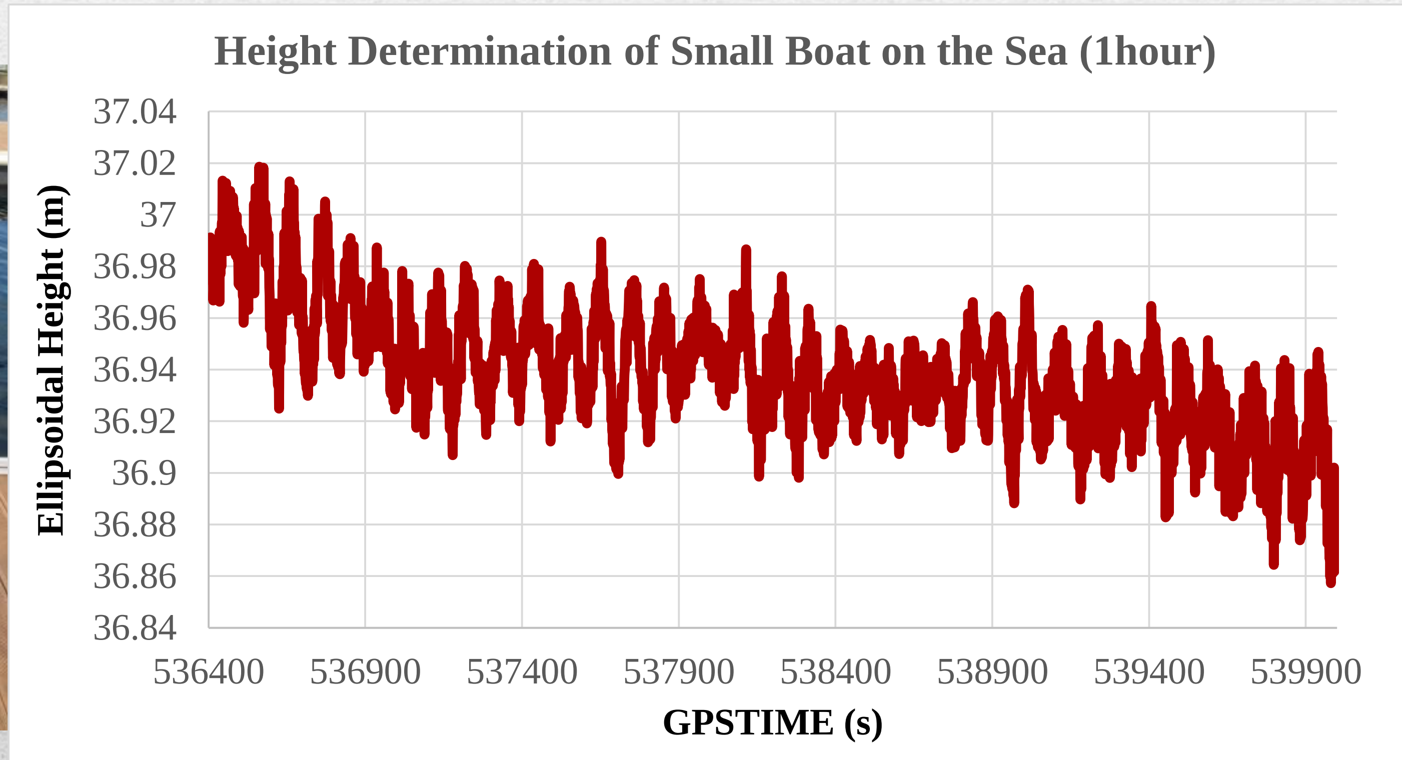
- Reference positions deduced from GPS/QZS/BeiDou/GLONASS with dual frequency @ 84% fix rate.
- Reliability % checked only if (result - reference position)=~ 50 cm.
- Average HDOP for only GPS approximately 4.3 while for GPS/BeiDou was 1.3.
- Fix rates dropped significantly compared to stationary tests
- Despite incorrect fixes, percentage of accurate results within 50 cm in horizontal direction jumped by adding BeiDou satellites.
- Similar tendency also observed for dual frequency case.

Low-cost receiver test using boat

-Single frequency GPS/QZS/BeiDou RTK-







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 8–9 satellites are generally required for only GPS constellation.

- Second reason: good selectability;

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

- For crane test, the mask angle was important for increasing fix rate.
- Avoiding the multipath reflections is quite important too.

Future Direction

- Ambiguity resolution with consideration of ISBs will be evaluated:

  Once correct ISBs are obtained, one reference satellite for multi-GNSS

- Autonomous UAV like waypoint-navigation is already available but it essentially does not need RTK:

  We are looking for the application using centimeter-accuracy RTK for small UAV

Thank you for your attention !