GNSS NLOS Pseudorange Correction based on Skymask for Smartphone Applications

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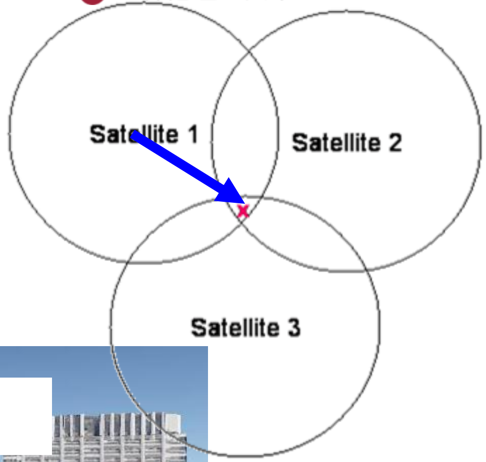
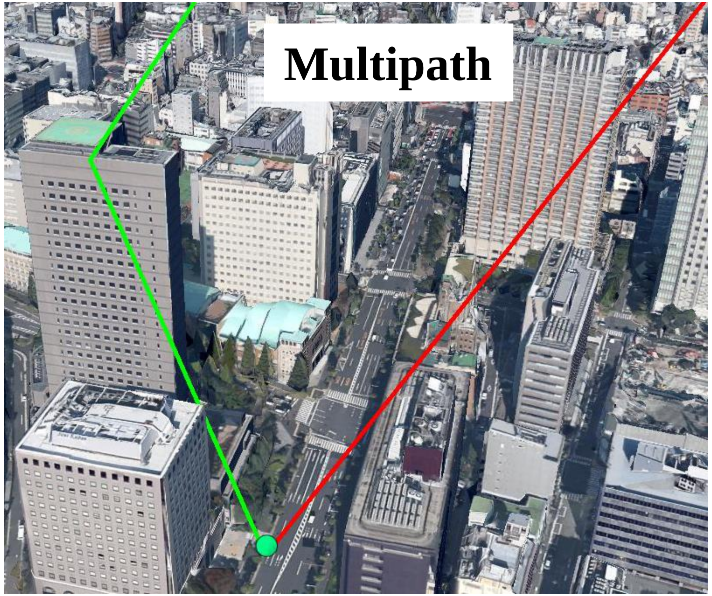
Session A1: Applications of Raw GNSS Measurements from Smartphones

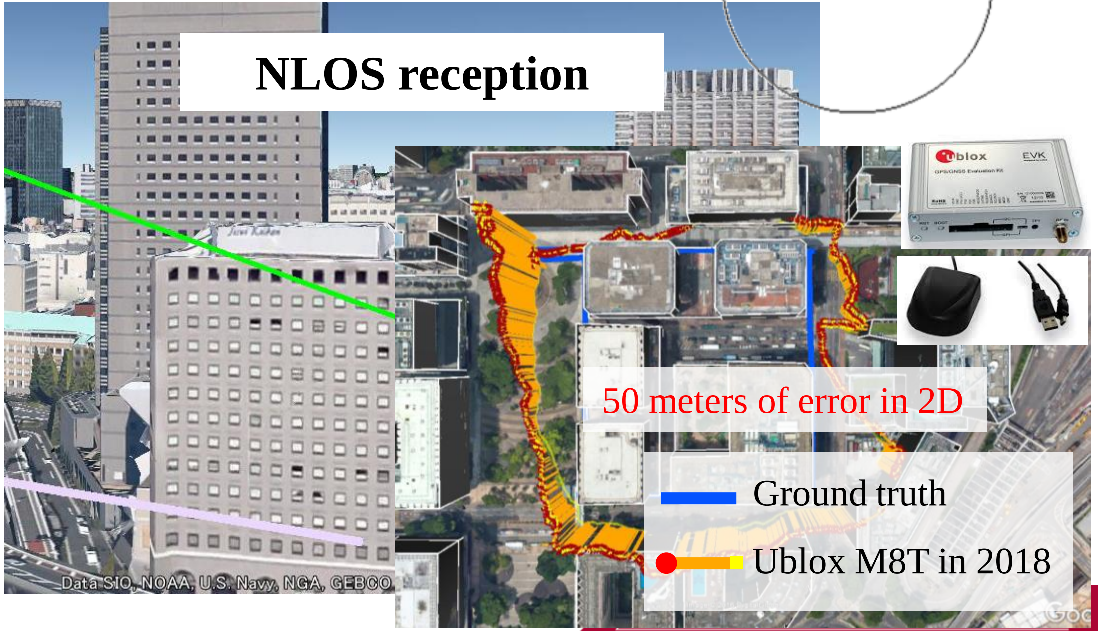
ION GNSS+ 2019, Miami, Florida

Background

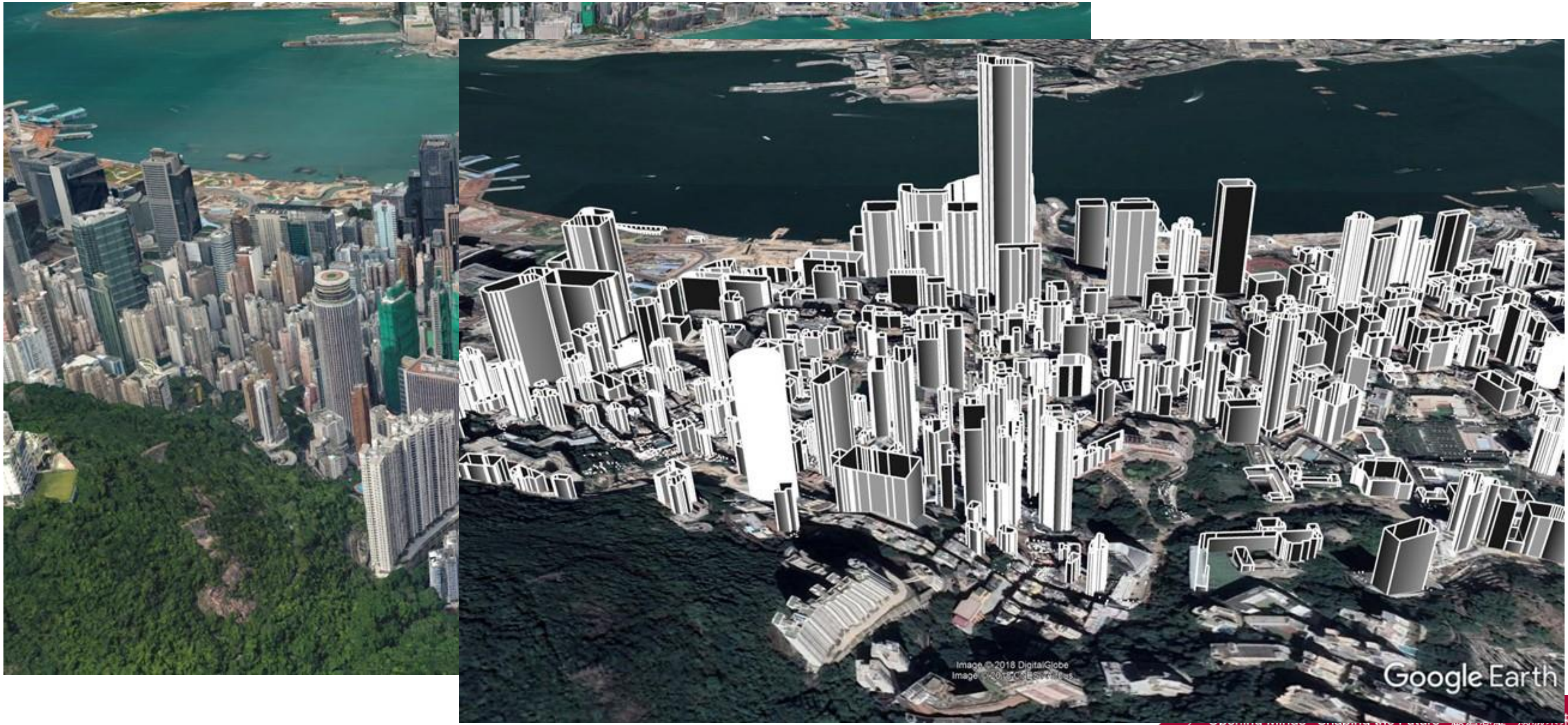
- GNSS Positioning is Triangulation.
- **Distance** between satellite and receiver is calculated by <u>time of transmission</u> × speed of light.





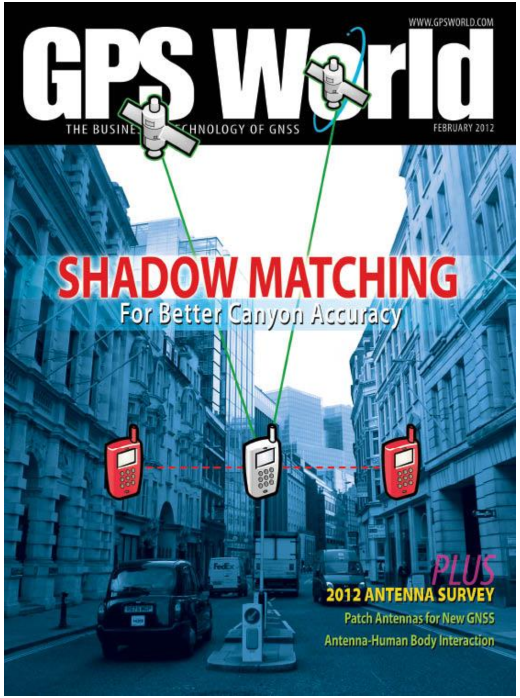


Widely available 3D building model now!



Popular 3DMA (3D mapping aided) GNSS

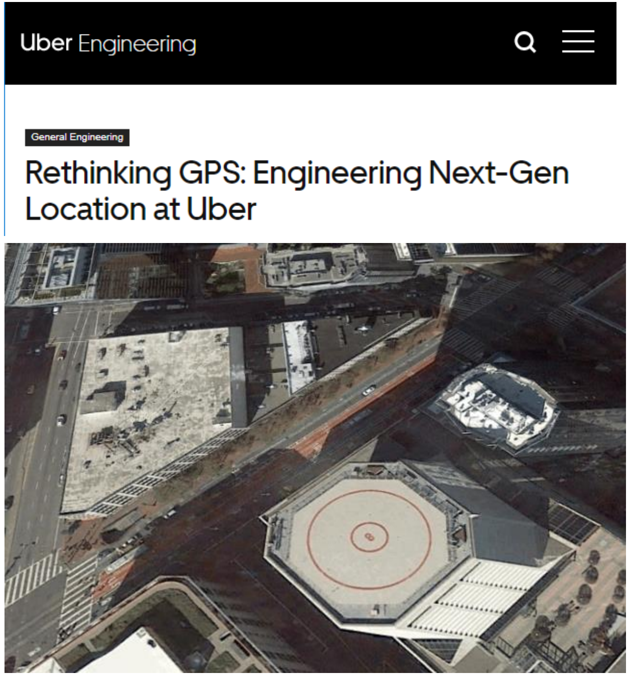
Shadow matching
(Satellite Visibility)



+

GNSS Ray-tracing
(Range and C/N_0)

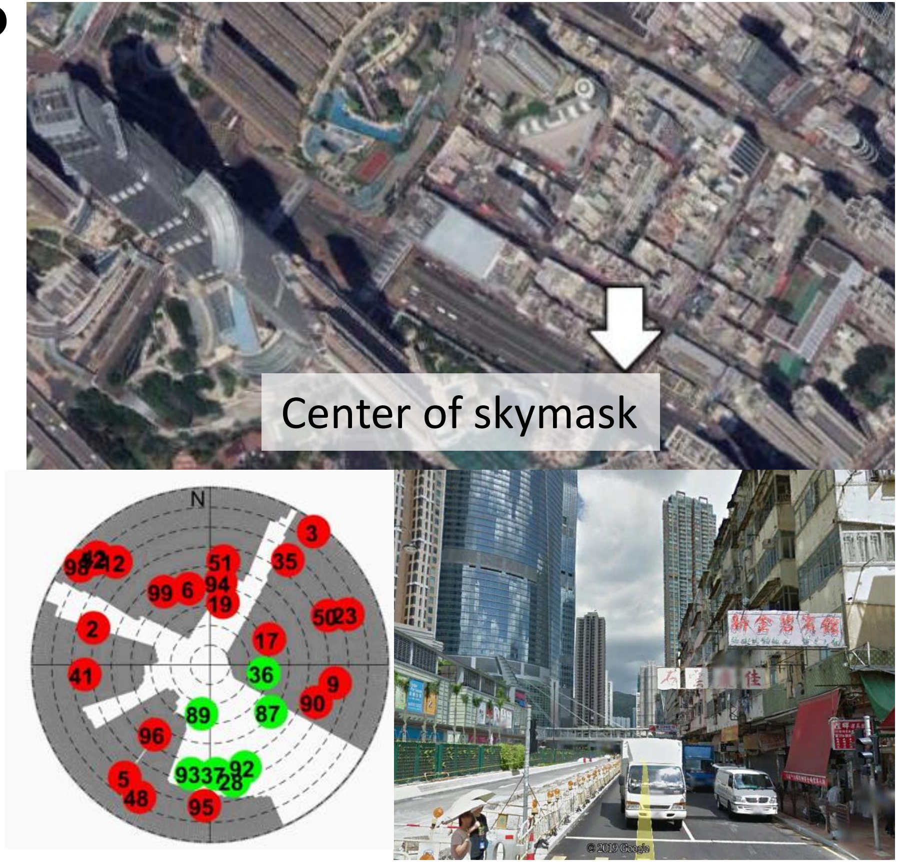
=



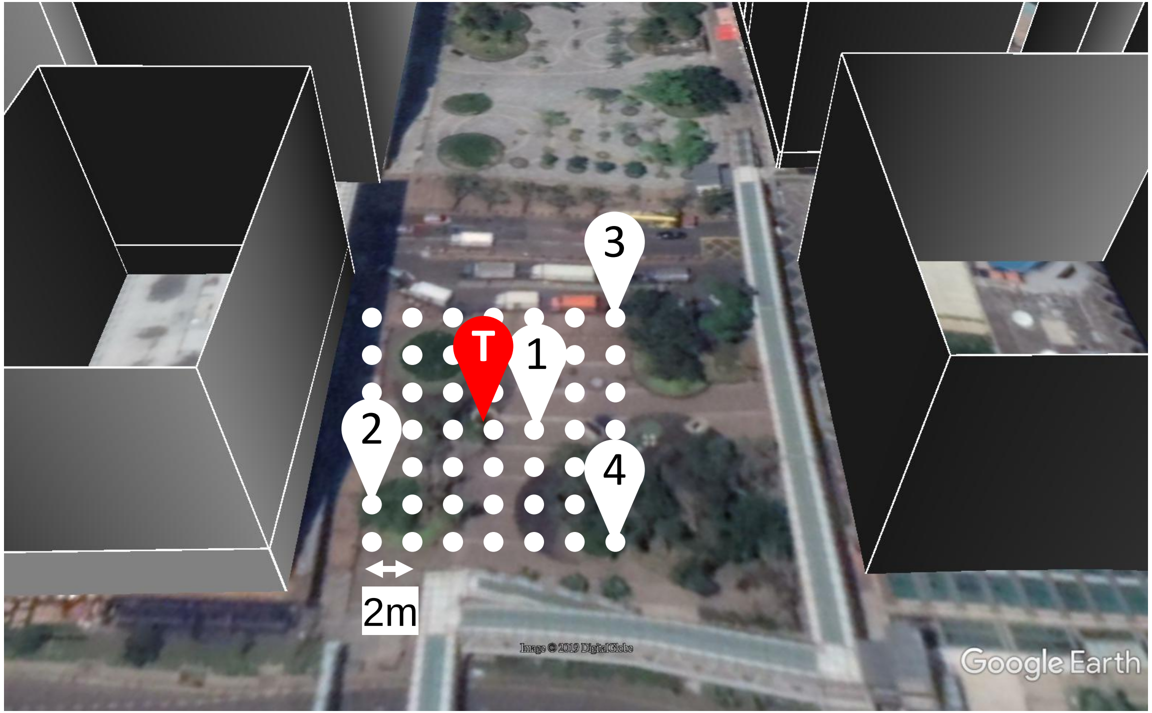
Rethinking GPS: Engineering Next-Gen Location at Uber

Ray-tracing is essential?

- Example: A typical urban canyon in Hong Kong.
- 20 out of 27 pseudorange measurements are affected by NLOS reflection (Mi8).
- **Instead of excluding or de-weighting** the NLOS measurement, we believe it is should be **corrected and used.**



Ray-Tracing 3DMA GNSS



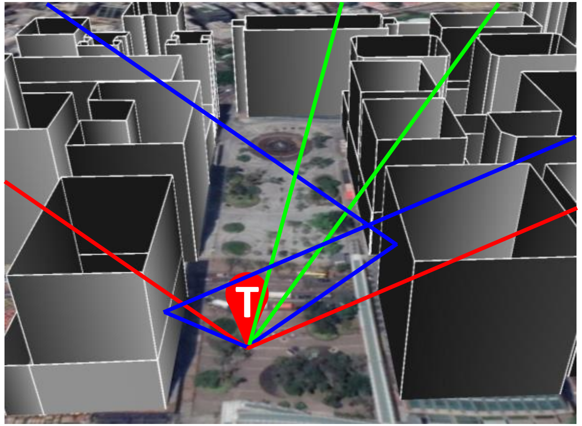
3D map aided positioning method is a Particle filter based method

Using
1. Positioning solution
2. Pseudorange
3. Signal strength

Candidate grid distribution
- Conventional GPS positioning method
- With 25m radius, 2m separation

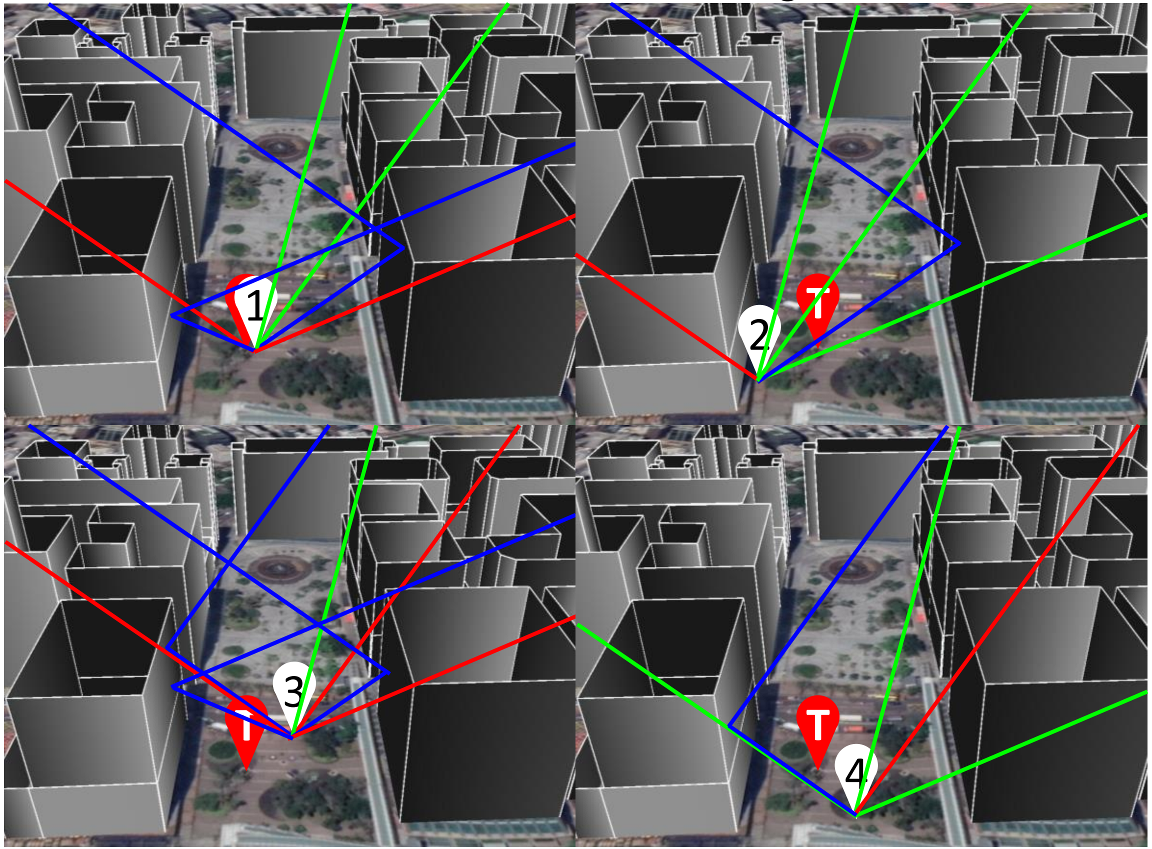
Ray-Tracing

Measurements

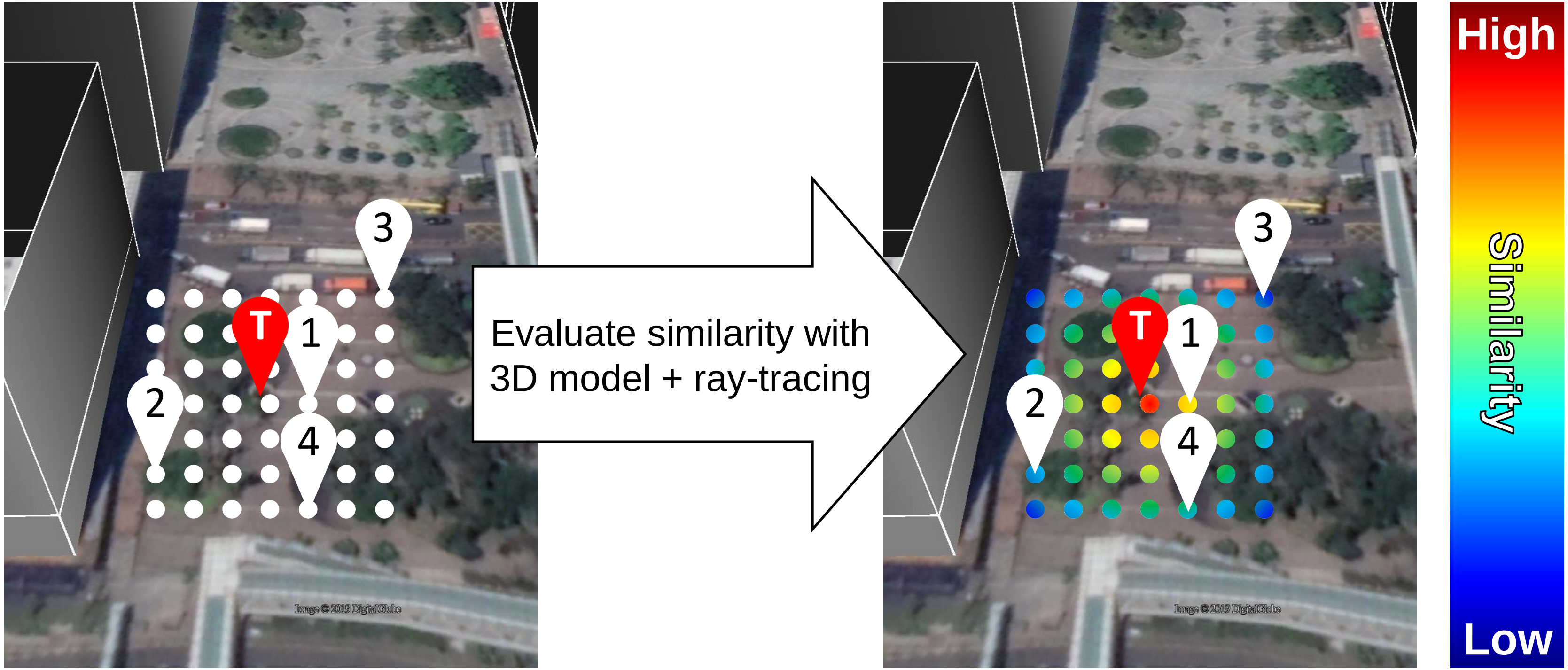


Candidate	Similarity
1	Very high
2	High
3	Low
4	Low

Simulated Pseudorange



Ray-Tracing 3DMA



Ray-tracing is computationally expensive!

Skymask 3DMA

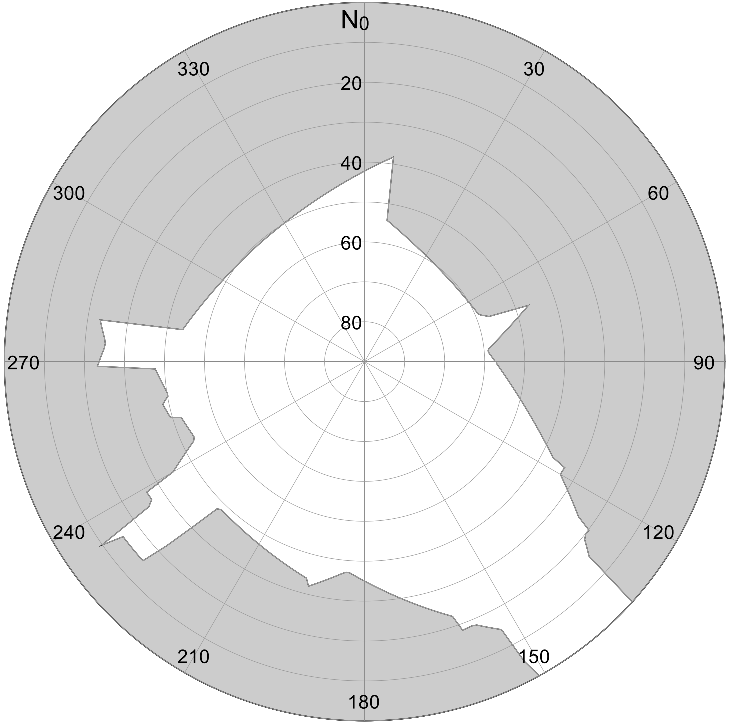
- Resource utilization (share resources with shadow matching)
- Provide NLOS correction
- Reduce computation load

Ng, H-F., Zhang, G., Hsu, Li-Ta, April 8-12, 2019, “Range-based 3D Mapping Aided GNSS with NLOS Correction based on Skyplot with Building Boundaries,” ION Pacific PNT 2019, Honolulu, HA, USA.

Skymask

- **Skymask**: surrounding building boundaries are projected on the skyplot
- 360 elevation angle represents corresponding azimuth angle
- Satellite falls into 'shadow' should be blocked

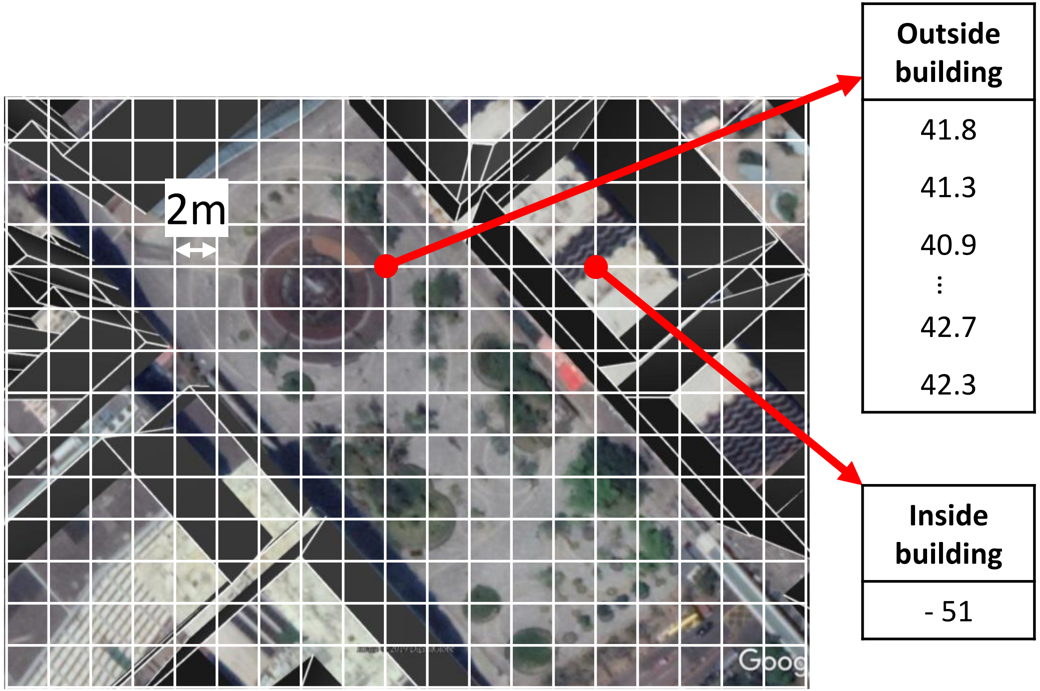
Azimuth (degree)	Elevation (degree)
1	41.8
2	41.3
3	40.9
…	…
359	42.7
360	42.3



Offline Process – Skymask Generation

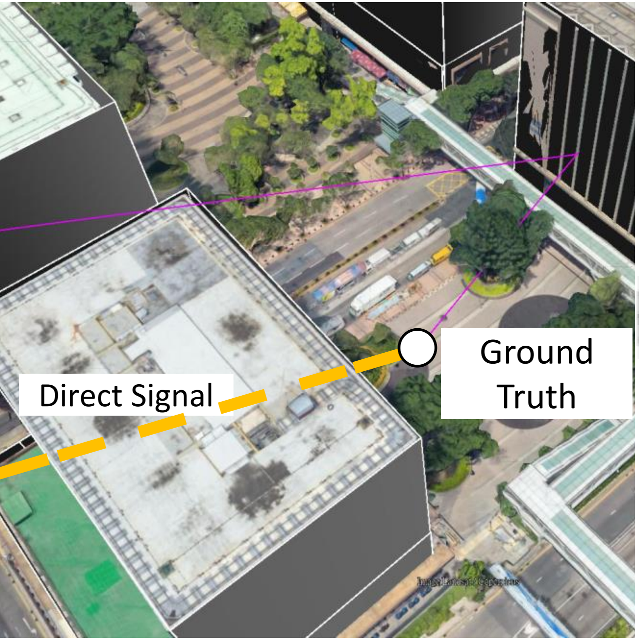
- **Skymask table**: area of grid points to store the skymask & building height information

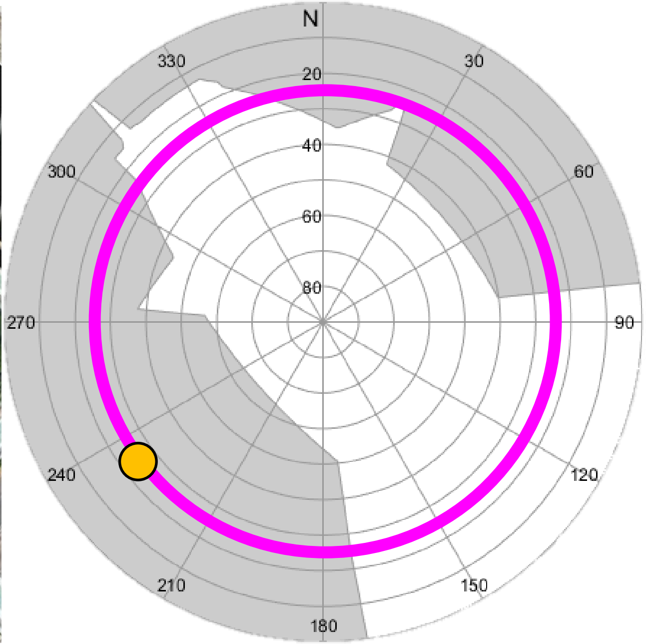
  - Outside building: skymask
  - Inside building: building height

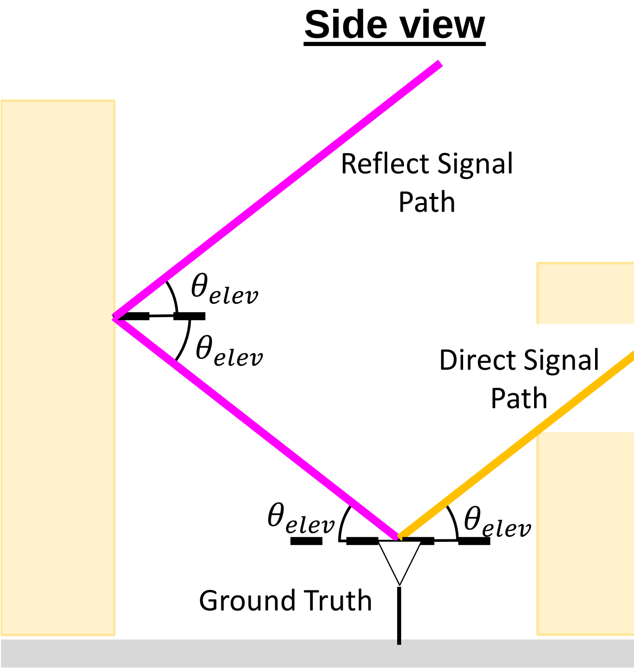


Detecting Reflecting Point From Skymask

- Finding elevation angle of reflecting point

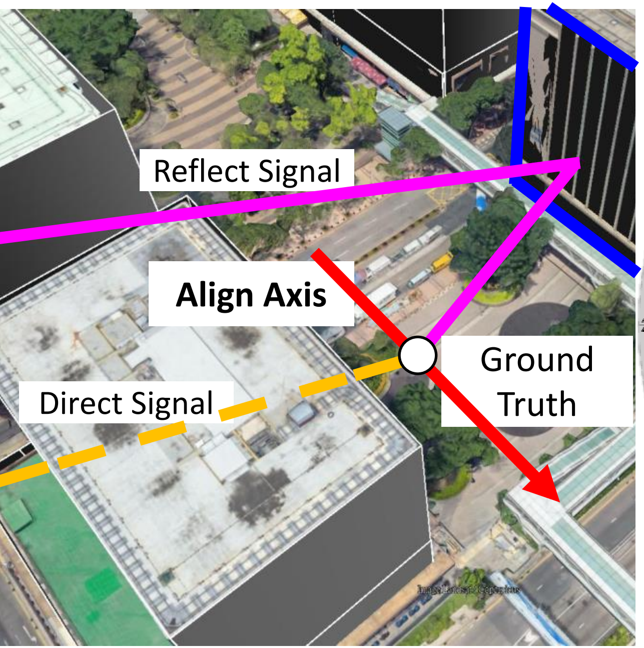


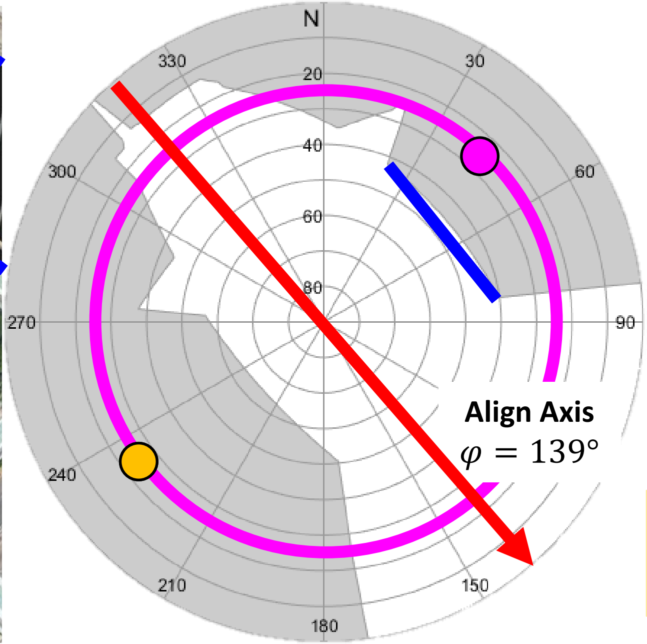




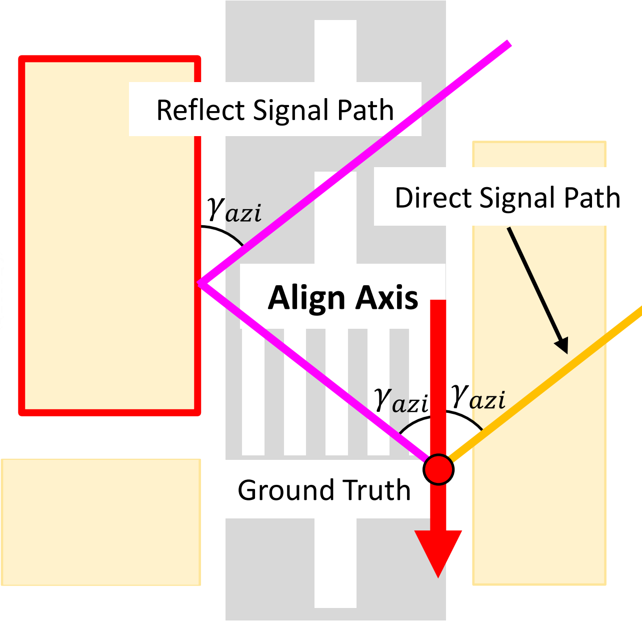
Detecting Reflecting Point From Skymask

- Finding azimuth angle of reflecting point



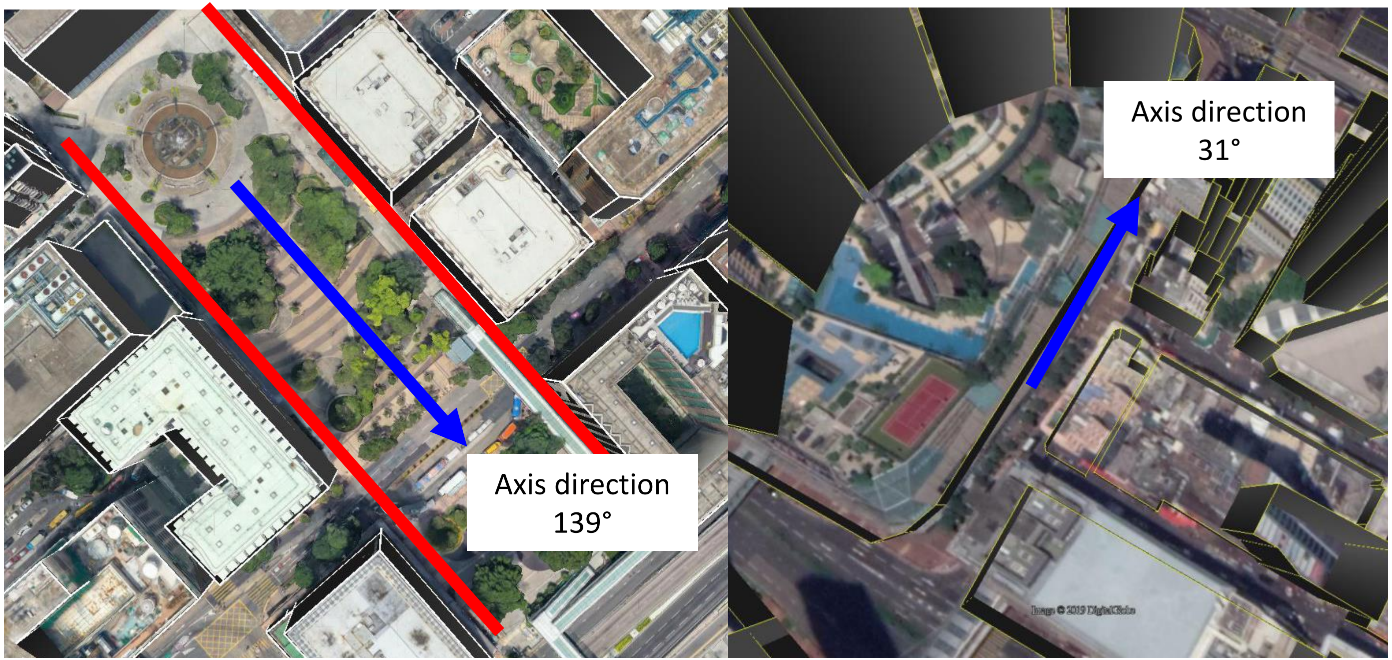


Top-down view



Detecting Reflecting Point From Skymask

- Align axis in 'tidy aligned' environment



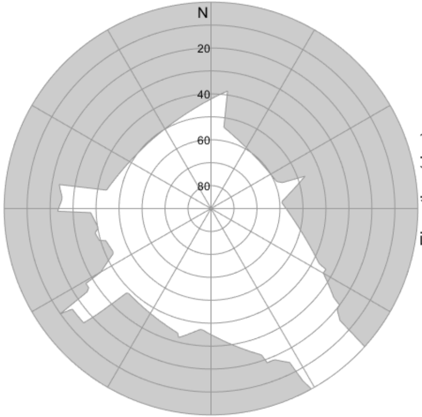
Ng, H-F., Zhang, G., Hsu, Li-Ta, April 8-12, 2019, "Range-based 3D Mapping Aided GNSS with NLOS Correction based on Skyplot with Building Boundaries," ION Pacific PNT 2019, Honolulu, HA, USA.

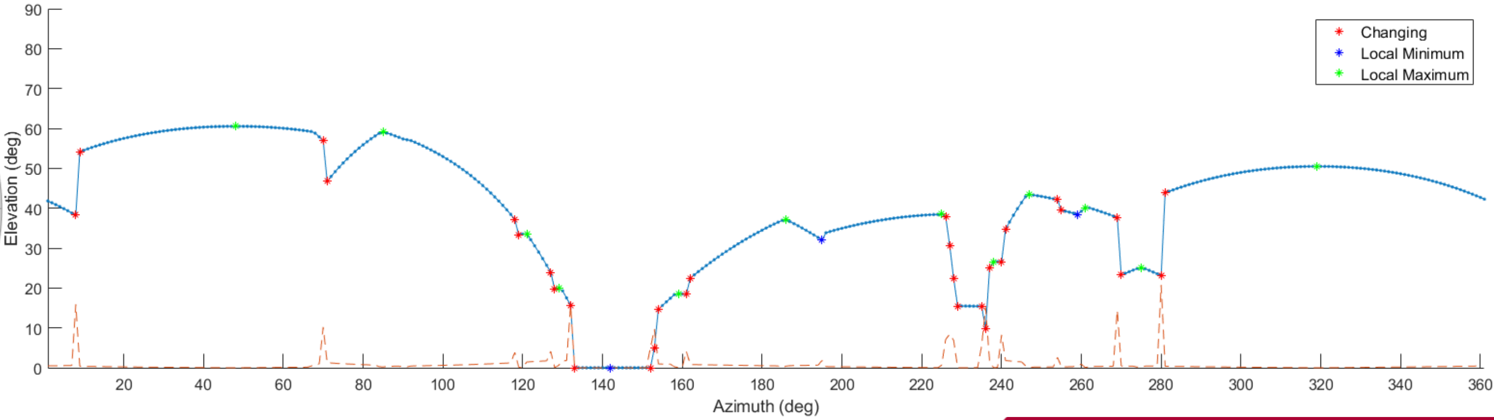
Determine Feature Points

Sudden change points - adjacent elevation > 2°, sudden jump on elevation angle, another building/new surface. If adjacent point labelled as 'changing point', not identify as a valid surface

Local minima, maxima - new surface

- Azimuth angles between two consecutive feature points will consider as one surface
- Except,
  1. Two adjacent azimuth are sudden change point
  2. Elevation angle is 0°





Azimuth Angle of Reflecting Plane (AARP) Determination

Candidate's Enhanced Skymask

↓

Determine feature points → 1. Sudden change point; 2. Local maximum/minimum

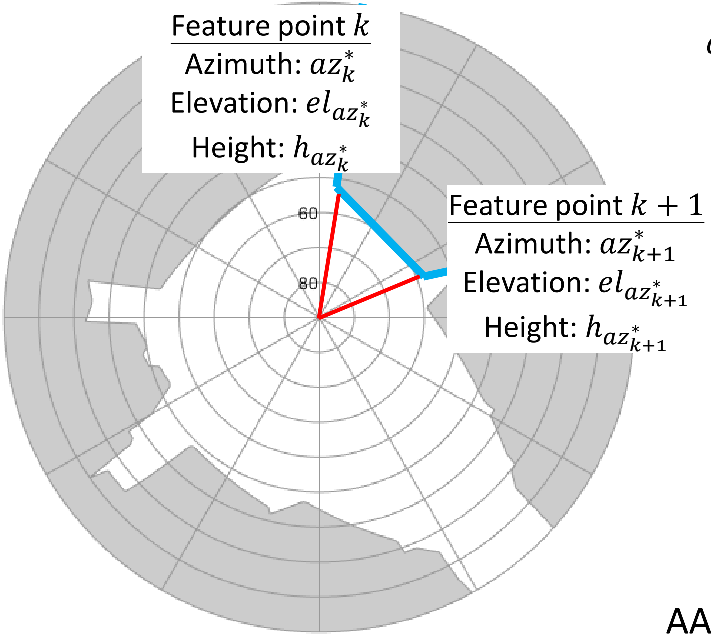
↓ Total K feature points

Calculate AARP on each azimuth angle: $\varphi_{az} = atan2(y_{k+1} - y_k, x_{k+1} - x_k)$

↓

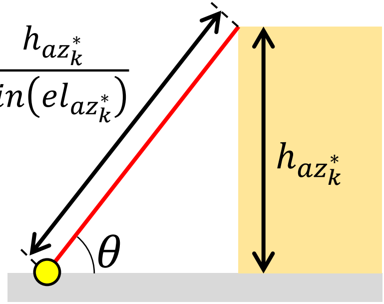
Predict incoming angle on each azimuth angle: $\psi_{az} = 2\varphi_{az} - az$

Calculate AARP & Predict Incoming Angle

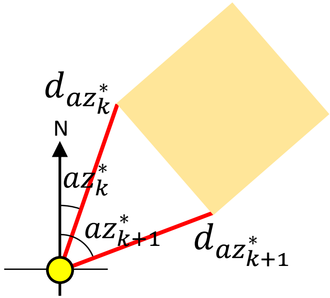


Side View

$$d_{az_k^*} = \frac{h_{az_k^*}}{sin(el_{az_k^*})}$$



Top View



Convert Feature point az^* from polar $(az_k^*, el_{az_k^*}, h_{az_k^*})$ coordinate to local coordinate (x_k, y_k, z_k)

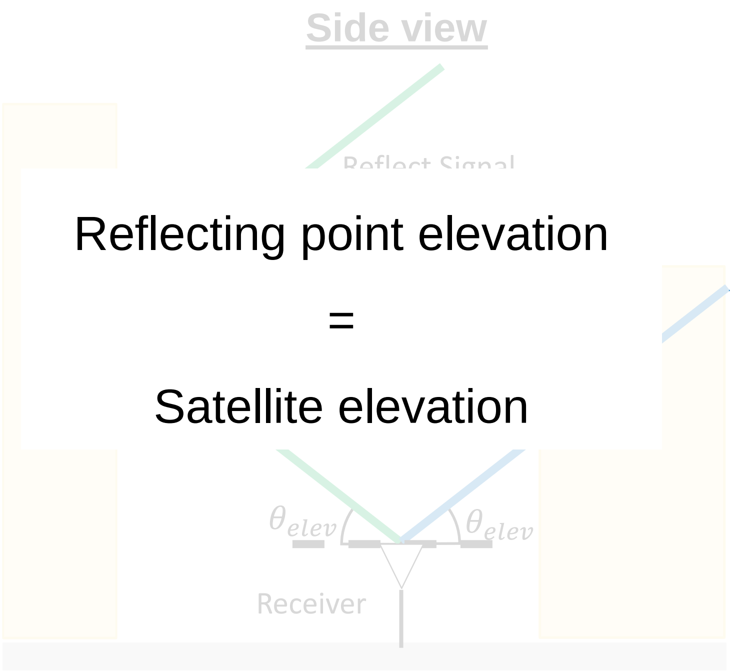
- North $x_k = \cos(az_k^*)\cos(el_{az_k^*})\, d_{az_k^*}$
- East $y_k = \sin(az_k^*)\cos(el_{az_k^*})\, d_{az_k^*}$
- Down $z_k = -h_{az_k^*}$

AARP φ_{az} for $az \in [az_k^*, az_{k+1}^*] = atan2(y_{k+1} - y_k, x_{k+1} - x_k)$

Predict incoming angle $\psi_{az} = 2\varphi_{az} - az$

Detecting Reflecting Point From Skymask

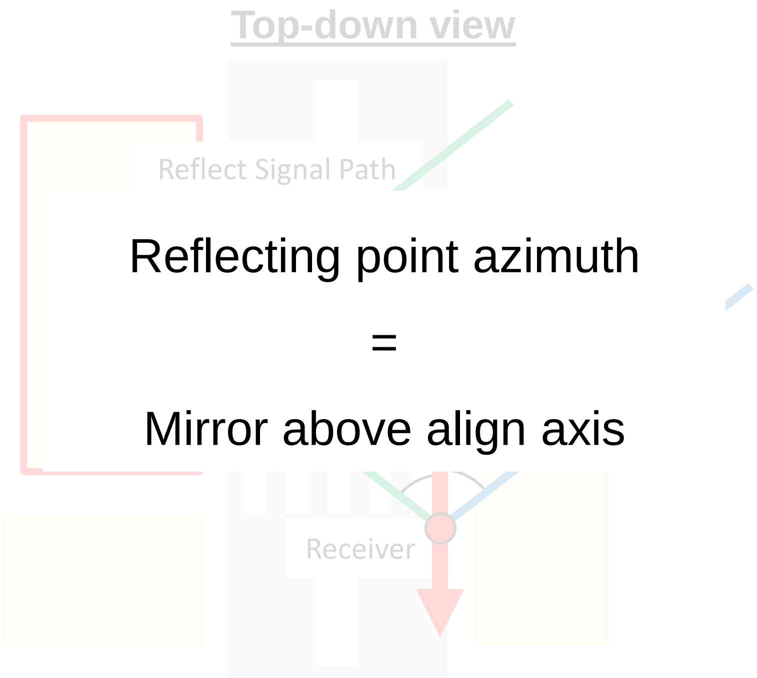
- Law of reflection



Reflecting point elevation

=

Satellite elevation



Reflecting point azimuth

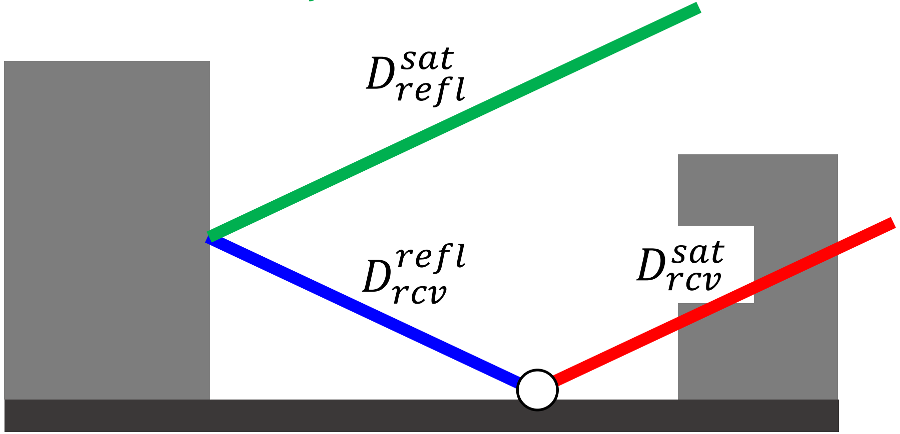
=

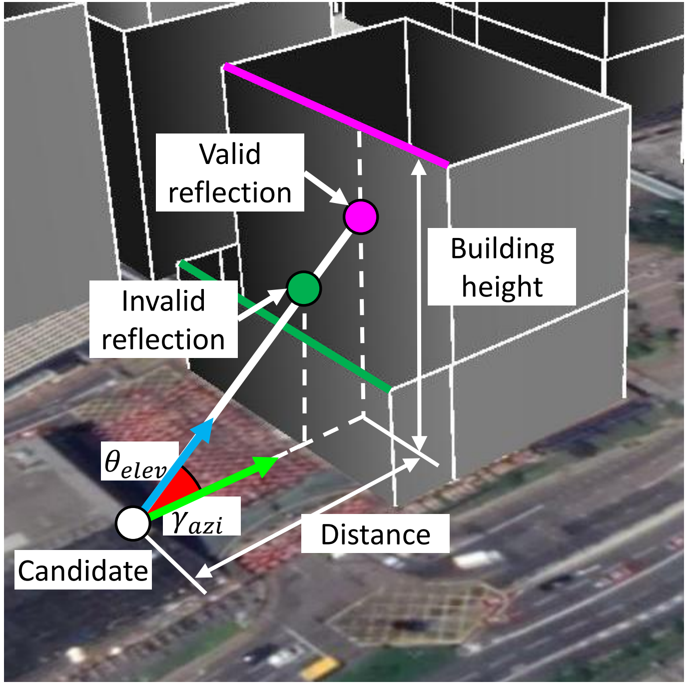
Mirror above align axis

Detecting Reflecting Point From Skymask

- Getting horizontal distance between candidate and reflecting point & reflecting point actual position
- Calculate NLOS reflection delay

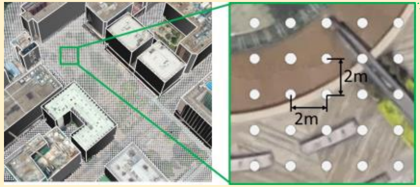
$$\varepsilon_n^{refl(i)} = D_{refl}^{sat} + D_{rcv}^{refl} - D_{rcv}^{sat}$$





Flowchart of the Proposed 3DMA GNSS

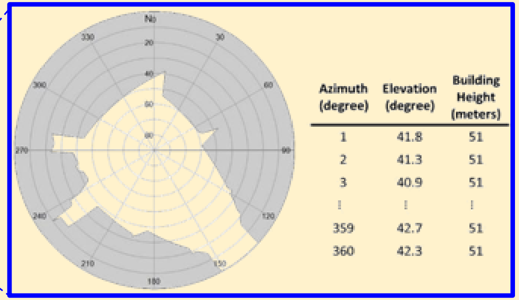
Offline Process



Digital terrain model → 2x2 meters grid in a selected area

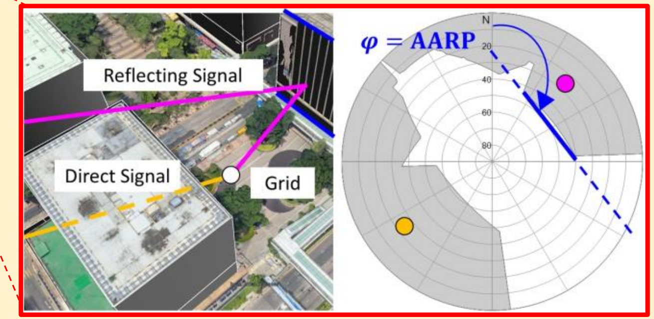
Broadcast ephemeris, 3D building models → Skyplot with building boundaries (Skymask)

2x2 meters grid in a selected area → Skyplot with building boundaries (Skymask)



Azimuth (degree)	Elevation (degree)	Building Height (meters)
1	41.8	51
2	41.3	51
3	40.9	51
⋮	⋮	⋮
359	42.7	51
360	42.3	51

Identify angle of the reflecting planes (AARP) of each building respect to a grid (Ng et al 2019)



GNSS Receiver measurement

Predict the satellite visibility and calculate reflection delay distance if the satellite detected as NLOS in the grid

Calculate simulated ranges from the grid and their difference between receiver measurements

Calculate of the likelihood of each grid by GNSS shadow matching (Groves et al 2019)

Calculate of the likelihood of each grid by likelihood-based 3DMA GNSS ranging (Groves et al 2019)

Calculate of the likelihood of each grid by the proposed Skymask 3DMA method

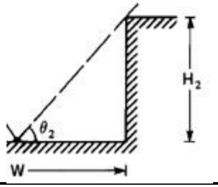
Determine positioning solution

Experiment Setup


(Samsung)


(Mi 8)

- Samsung Galaxy Note 8 (Qualcomm Snapdragon 835), G/E/B – single freq.
- Xiaomi Mi 8 (Broadcom BCM47755 chip), G/R/E/B – single freq. (we used)
- Output rate: 1 Hz



Experiment	Duration (seconds)	Building height to street width ratio ($\frac{building\ height}{street\ width}$)
1: static	687	2.17
2: static	605	2.81
3: static	916	3.88
4: dynamic	66	0.68
5: dynamic	101	2.83

Methods compared

[1] E. Realini and M. Reguzzoni, “GoGPS: open source code”, 2013.
[2] P. Groves and M. Adjrad, "Performance Assessment of 3D-Mapping-Aided GNSS - Part 1: Algorithms, User Equipment and Review," *Navigation: Journal of the Institute of Navigation*, 2019
[3] P. Groves and M. Adjrad, "Likelihood-based GNSS positioning using LOS/NLOS predictions from 3D mapping and pseudoranges," *GPS Solutions*, 2017.

- WLS: weighted-least-squared [1]
- SDM: GNSS shadow matching [2]
- LBR: likelihood-based 3DMA GNSS ranging [3]
- SKY: the proposed skymask 3DMA GNSS
- SDM + LBR: hypothesis domain integration of shadow matching and likelihood-based 3DMA GNSS ranging [2] $\Lambda_i = \Lambda_{i,SDM} \cdot \Lambda_{i,LBR}$
- SDM + SKY: hypothesis domain integration of shadow matching and skymask 3DMA $\Lambda_i = \Lambda_{i,SDM} \cdot \Lambda_{i,SKY}$
- SDM + LBR + SKY: hypothesis domain integration of shadow matching, likelihood-based 3DMA GNSS ranging, and skymask 3DMA

$$\Lambda_i = \Lambda_{i,SDM} \cdot \Lambda_{i,LBR} \cdot \Lambda_{i,SKY}$$

Experiment 1 – Static – H/W 2.17

Receiver	RMS error (m)	NMEA	WLS	SDM	LBR	SKY	SDM + LBR	SDM + SKY	SDM + LBR + SKY
Xiaomi Mi 8	2D	34.64	32.15	31.48	23.96	24.94	21.05	23.67	17.35
	Along street	5.52	17.83	19.71	7.19	5.94	6.39	7.56	6.64
	Across street	34.19	26.75	24.54	22.85	24.22	20.06	22.43	16.03
Samsung Galaxy Note 8	2D	20.49	118.32	11.46	14.94	15.46	14.95	12.47	14.37
	Along street	4.17	42.88	8.00	8.90	9.06	10.13	5.67	11.37
	Across street	20.06	110.27	8.21	12.00	12.53	11.00	11.11	8.79

Experiment 2 – Static – H/W 2.81

Receiver	RMS error (m)	NMEA	WLS	SDM	LBR	SKY	SDM + LBR	SDM + SKY	SDM + LBR + SKY
Xiaomi Mi 8	2D	5.95	18.77	6.13	7.19	7.38	5.73	5.87	5.66
	Along street	2.08	9.16	5.89	3.50	1.67	3.27	1.55	3.40
	Across street	5.58	16.38	1.70	6.28	7.19	4.70	5.67	4.52
Samsung Galaxy Note 8	2D	12.10	132.40	5.55	17.03	13.31	17.24	11.44	19.13
	Along street	7.21	73.70	4.23	6.10	5.28	6.04	4.35	6.15
	Across street	9.72	110.00	3.60	15.90	12.22	16.15	10.58	18.11

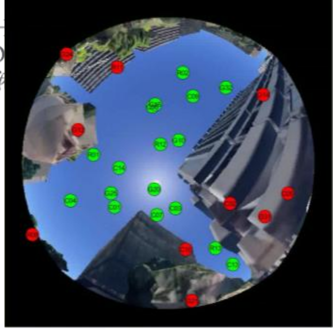
Experiment 3 – Static – H/W 3.88

Receiver	RMS error (m)	NMEA	WLS	SDM	LBR	SKY	SDM + LBR	SDM + SKY	SDM + LBR + SKY
Xiaomi Mi 8	2D	14.61	26.61	11.54	18.51	17.25	15.53	14.22	12.79
	Along street	7.64	17.56	10.24	5.38	5.49	6.20	6.30	6.66
	Across street	12.45	20.00	5.32	17.71	16.35	14.24	12.74	10.92
Samsung Galaxy Note 8	2D	6.64	115.72	17.10	19.55	6.99	17.66	5.26	18.28
	Along street	5.83	67.28	17.01	17.44	6.11	16.21	4.76	16.64
	Across street	3.17	94.16	1.78	8.84	3.39	7.01	2.23	7.58

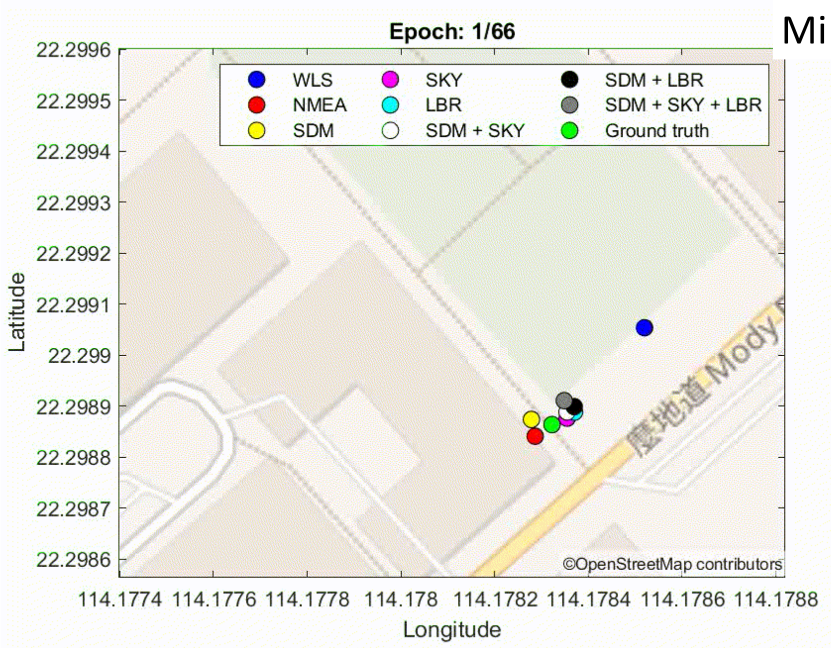
Experiment 4 – Dynamic – H/W 0.68

Receiver	RMS error (m)	NMEA	WLS	SDM	LBR	SKY	SDM + LBR	SDM + SKY	SDM + LBR + SKY
Xiaomi Mi 8	2D	3.27	38.67	8.18	12.55	10.45	14.47	11.79	13.70
	Along street	1.82	7.22	5.53	5.91	1.12	6.42	1.37	5.57
	Across street	2.72	37.99	6.03	11.08	10.39	12.97	11.71	12.51
Samsung Galaxy Note 8	2D	3.13	114.62	7.16	23.60	10.23	21.34	12.79	23.15
	Along street	2.23	98.43	4.02	12.87	3.44	11.47	4.04	12.65
	Across street	2.20	58.73	5.93	19.78	9.63	17.99	12.14	19.39

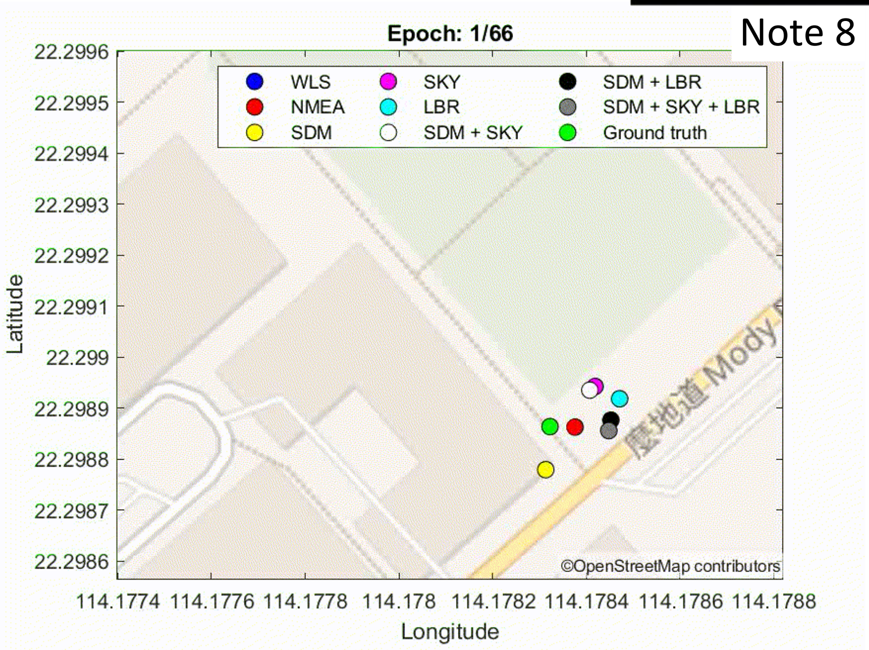
Experiment 4 – Dynamic – H/W 0.68



Mi 8

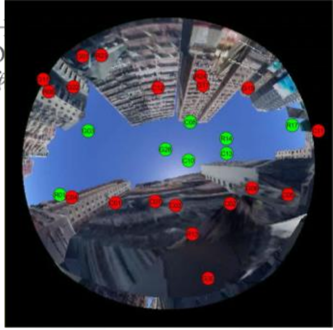


Note 8



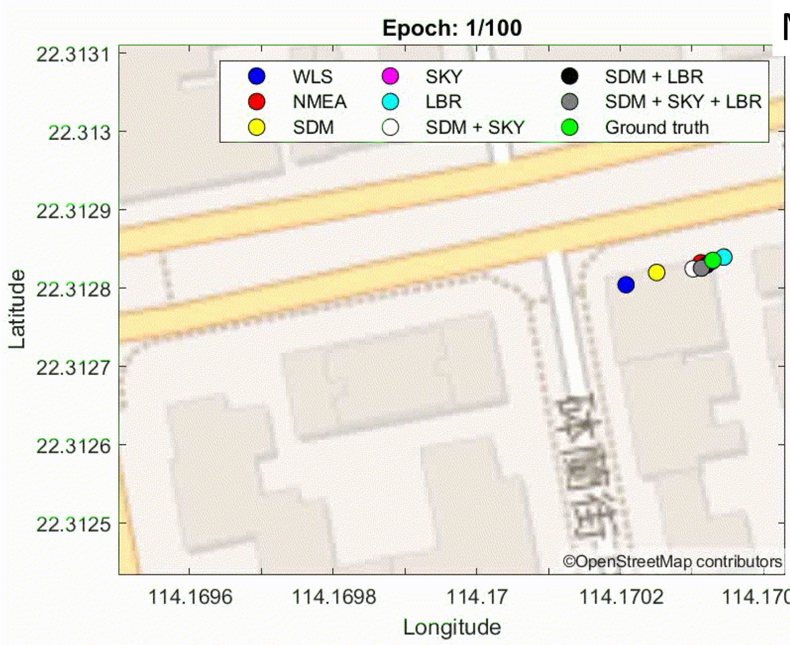
Experiment 5 – Dynamic – H/W 2.83

Receiver	RMS error (m)	NMEA	WLS	SDM	LBR	SKY	SDM + LBR	SDM + SKY	SDM + LBR + SKY
Xiaomi Mi 8	2D	6.64	18.33	5.68	5.65	6.31	4.89	5.21	5.27
	Along street	3.39	14.57	4.51	5.01	5.75	4.67	4.93	4.90
	Across street	5.70	11.12	3.45	2.61	2.60	1.45	1.69	1.95
Samsung Galaxy Note 8	2D	4.50	165.52	7.91	9.96	5.20	10.60	5.97	12.13
	Along street	1.74	157.49	7.49	7.31	4.72	7.93	5.80	9.70
	Across street	4.15	50.91	2.55	6.76	2.20	7.03	1.43	7.28

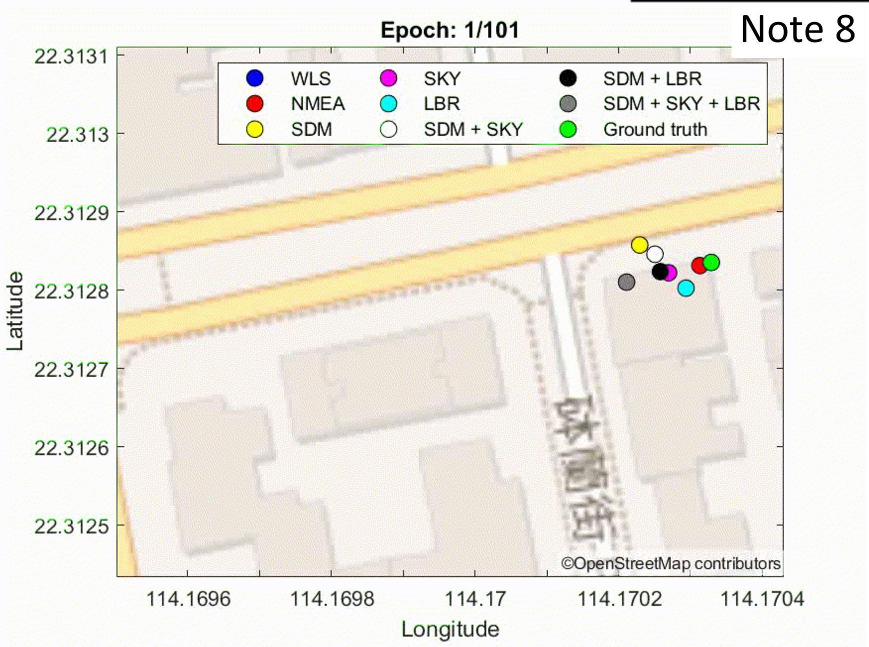


Experiment 5 – Dynamic – H/W 2.83

Mi 8



Note 8



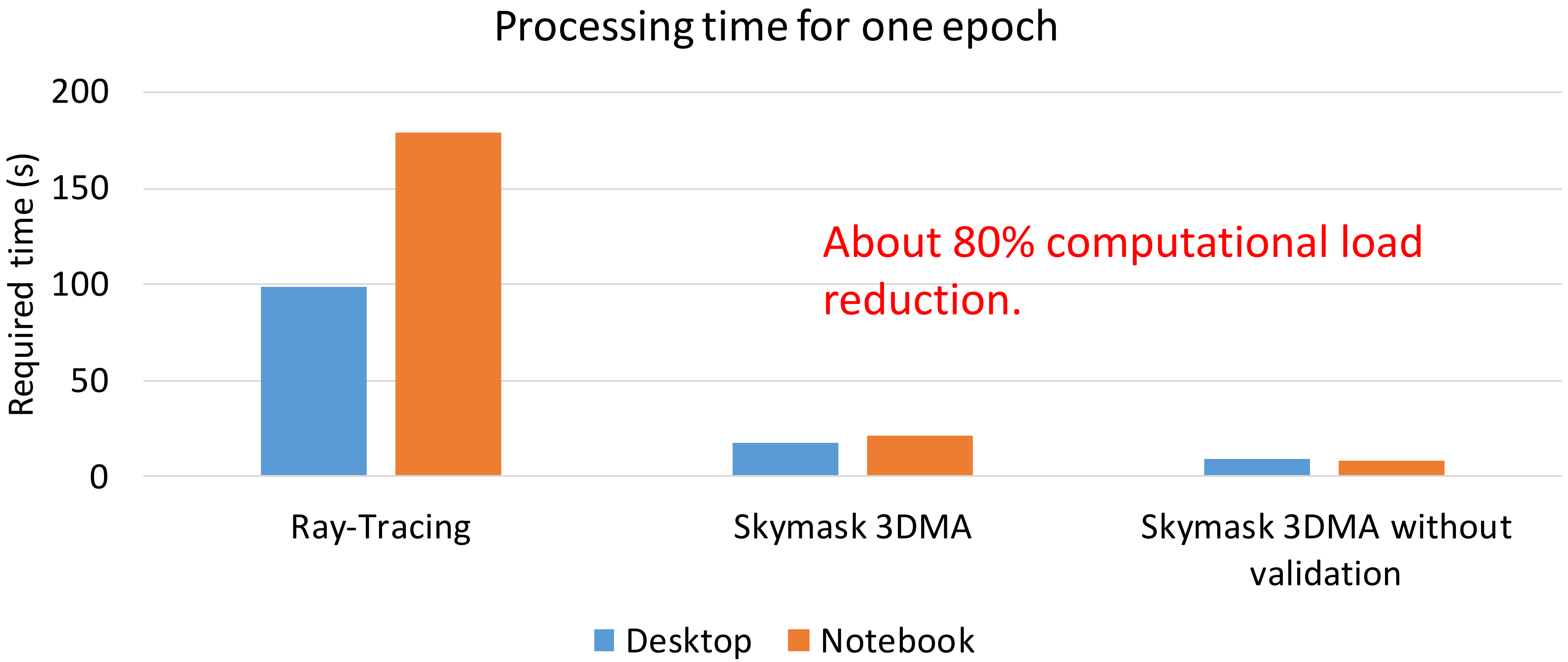
NLOS reflection delay identified by three methods. In the case of H/W about 3

		Mean (m)	S.D. (m)
PRN 97 (TST)	Actual NLOS delay*	44.77	4.24
	Proposed skymask 3DMA	46.23	0.09
	Ray-tracing	44.2	0.08
PRN 93 (TW)	Actual NLOS delay*	8.15	2.17
	Proposed skymask 3DMA	8.13	0.01
	Ray-tracing	6.29	0.00

* Calculated by double-differencing the measurements from smartphone and reference station (Xu et al, 2019).

Xu B., Jia Q., Luo Y., Hsu, L.T.* (2019) Intelligent GPS L1 LOS/Multipath/NLOS Classifiers Based on Correlator-, RINEX-and NMEA-Level Measurements, *Remote Sensing*, 11(16):1851.

Comparison of Computation Load



Conclusions

- SDM+ SKY is stable even when the pseudorange measurement quality is not as good. (which LBR has higher requirement on it)
- When Height to Width (H/W) ratio is about 3, the proposed Skymask 3DMA GNSS is very effective. (due to the single-reflected NLOS).

Future Work

- To develop context awareness algorithm to classify the area that 3DMA GNSS is effective.
- To explore the potential of 3DMA GNSS in static RTK for the initial point of mobile mapping system.

Thank you for your attention ☺

Q&A

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