Precise positioning on smartphones

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10 September 2021

ASNAT-19

Outline

- Organization
- Google Smartphone Decimeter Challenge
- Proposed solution
- Mathematical models
- Measurement analysis
- Results
- Conclusions / Future work

Organization

- Collaboration between CS Group and ENAC.
- Participation in the Google Smartphone Decimeter Challenge.
- **CS Group:** information-technology service company.
  - Expertise in Space Technologies.
  - Expertise in Android development.
- **ENAC:**
  - Expertise in Navigation.

Google Smartphone Decimeter Challenge

- **Objective:** Obtain best positioning accuracy from Android GNSS raw measurements.
- **Score:** Mean of 50 and 95 horizontal error percentiles.

Dataset	Train	Test
Campaigns	29	19
Traces	73	48
Phones	Pixel4, Pixel4Modded, Pixel4XL, Pixel4XLModded, Pixel5, Mi8, SamsungS20Ultra	Pixel4, Pixel4Modded, Pixel4XL, Pixel4XLModded, Pixel5, Mi8, SamsungS20Ultra
Ground-truth	Yes	No

Proposed solution

- RTK (float ambiguity solution). OSR from Verizon Inc.[1]
  - ⇨ Precise positioning solution.
  - ⇨ Lower convergence time than PPP.
- Doppler shift ⇨ Velocity estimation, smooth ranging measurements noise.
- Dual frequency measurements ⇨ Redundancy.
- 3 constellations: GPS, Galileo, BeiDou ⇨ Redundancy, better geometry.
- **Multiple receiver** ⇨ Improve accuracy, provide attitude estimation.[2]
- **Outlier rejection** ⇨ Reduce multipath effects, detect cycle slip.[3]
- **Sequential KF implementation** ⇨ Reduced execution time, simplified implementation.[4]

1. webscope.sandbox.yahoo.com/
2. X. Hu, P. Thevenon, and C. Macabiau, "Attitude determination and RTK performances amelioration using multiple low-cost receivers with known geometry," in *Proceedings of the 2021 International Technical Meeting of The Institute of Navigation*, 2021, pp. 439–453.
3. J.-G. Wang *et al.*, "Test statistics in kalman filtering," *Positioning*, vol. 1, no. 13, 2008.
4. D. Simon, *Optimal state estimation: Kalman, H infinity, and nonlinear approaches.* John Wiley & Sons, 2006.

Mathematical models

Positioning methods used

- **Single-Point Positioning:** Pseudorange.
- **Single-Point Positioning and Velocity:** Pseudorange + Doppler shift.
- **Single-receiver RTK:** DD Pseudorange + DD Carrier phase + Doppler shift.
- **Multiple-receiver RTK:** DD Pseudorange + DD Carrier phase + Doppler shift.

Single-receiver RTK

- **State vector:** $\boldsymbol{x} = \begin{bmatrix} \boldsymbol{b}_{us}^{T} & \dot{\boldsymbol{u}}^{T} & c\dot{\delta}t_{u} & c\dot{\boldsymbol{\delta t}}_{IF}^{T} & c\dot{\boldsymbol{\delta t}}_{IS}^{T} & \boldsymbol{N}^{SD^{T}} \end{bmatrix}^{T}$
- **State transition model:** Random walk model
- **Measurement vector:** $\boldsymbol{z} = \begin{bmatrix} \boldsymbol{\rho}^{DD^{T}} & \boldsymbol{\phi}^{DD^{T}} & \dot{\boldsymbol{\rho}}^{T} \end{bmatrix}$
- **Measurement noise:**

$$\boldsymbol{R}_{\rho^{SD}} = 2\boldsymbol{R}_{\rho} \qquad \boldsymbol{R}_{\rho^{DD}} = \boldsymbol{D}\boldsymbol{R}_{\rho^{SD}}\boldsymbol{D}^{T}$$

$$\boldsymbol{R}_{\phi^{SD}} = 2\boldsymbol{R}_{\phi} \qquad \boldsymbol{R}_{\phi^{DD}} = \boldsymbol{D}\boldsymbol{R}_{\phi^{SD}}\boldsymbol{D}^{T}$$

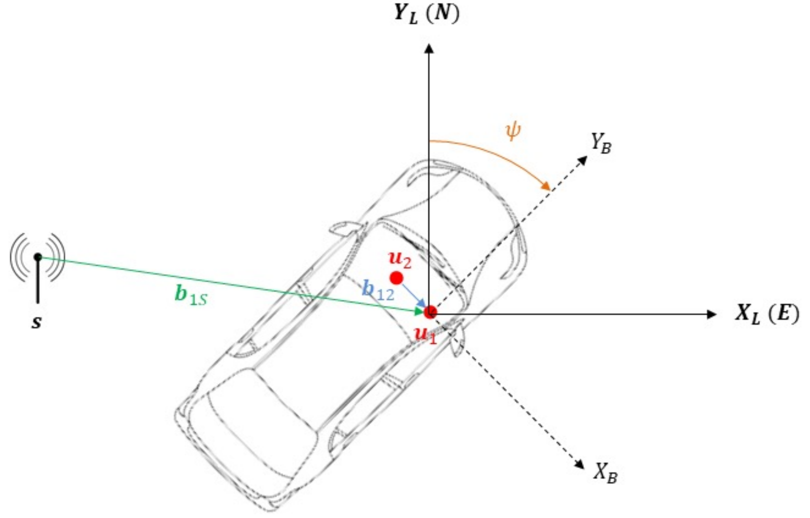
$$\boldsymbol{D} = \begin{bmatrix} -1 & 0 & \cdots & 0 & 1 \\ 0 & -1 & \cdots & 0 & 1 \\ \vdots & \vdots & \ddots & \cdots & \vdots \\ 0 & 0 & \cdots & -1 & 1 \end{bmatrix}$$

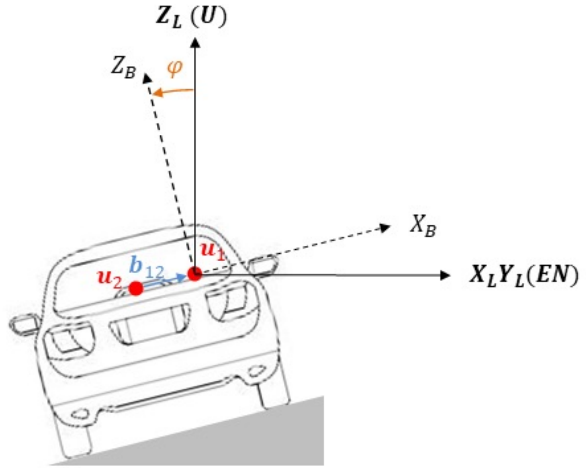
- Resulting measurement covariance matrix is non-diagonal ⇨ Problem for sequential KF.
- Accuracy of estimation was reduced when performing diagonalization with Cholesky.
- Alternative: Use diagonal matrix with inflated DD noise.

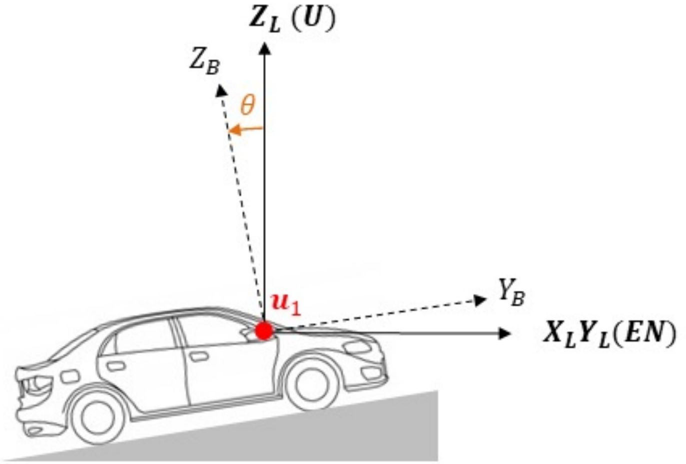
Multiple-receiver RTK

Multiple-receiver geometry:

$$\boldsymbol{b}_{12}^{E}(\theta, \varphi, \psi) = \boldsymbol{C}_{L2E}\boldsymbol{C}_{B2L}(\theta, \varphi, \psi)\boldsymbol{b}_{12}^{B}$$







Multiple-receiver RTK

- **State vector:**

$$x = \left[b_{1s}^{E\,T} \quad \theta \quad \varphi \quad \psi \quad \dot{u}_1^{E\,T} \quad \delta t_1 \quad \delta t_2 \quad \dot{\delta t}_{IF}^T \quad \dot{\delta t}_{IS}^T \quad N_{1s}^{SD\,T} \quad N_{2s}^{SD\,T} \right]^T$$

- **Measurement vector:**

$$z = \left[\rho_1^{DD\,T} \quad \rho_2^{DD\,T} \quad \phi_1^{DD\,T} \quad \phi_2^{DD\,T} \quad \dot{\rho}_1{}^T \quad \dot{\rho}_2{}^T \right]$$

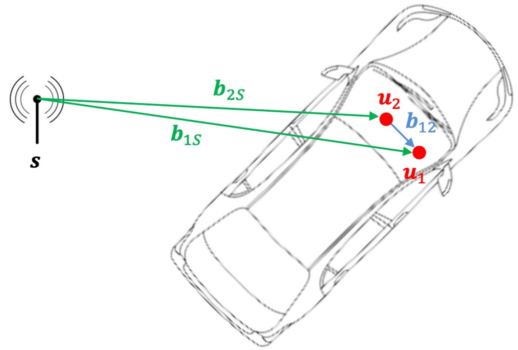
- **Measurement model:**

$$h_{\rho_2}(x)_{[j:]} = \left(e_{s,p} - e_{s,j}\right)^T (b_{2s}^E) = \left(e_{s,p} - e_{s,j}\right)^T (b_{1s}^E - b_{12}^E)$$

$$h_{\phi_2}(x)_{[j:]} = \left(e_{s,p} - e_{s,j}\right)^T (b_{1s}^E - b_{12}^E) + \lambda\left(N_p^{SD} - N_j^{SD}\right)$$

$$h_{\dot{\rho}_2}(x)_{[i]} = (\dot{s}_i - \dot{u}_2)^T e_i + c\dot{\delta t}_{u_2} + c\dot{\delta t}_{IF,i} + c\dot{\delta t}_{IS,i}$$

$$\boxed{(b_{1s}^E - b_{12}^E) = (b_{1s}^E - C_{L2E}(u) C_{B2L}(\theta, \varphi, \psi) b_{12}^B)}$$



Multiple-receiver RTK

- Measurement matrix for pseudorange and carrier phase:

$$\boldsymbol{H}_{\rho_2^{DD}[j:]} = \left[\left(\boldsymbol{e}_{s,p} - \boldsymbol{e}_{s,j}\right)^T \quad h_{\theta,2} \quad h_{\varphi,2} \quad h_{\psi,2} \quad 0 \quad \cdots \quad 0\right]$$

$$\boldsymbol{H}_{\phi_2^{DD}[j:]} = \left[\left(\boldsymbol{e}_{s,p} - \boldsymbol{e}_{s,j}\right)^T \quad h_{\theta,2} \quad h_{\varphi,2} \quad h_{\psi,2} \quad 0 \quad \cdots \quad 0 \quad \boldsymbol{\lambda}_j^T\right]$$

$$h_{\psi,2} = \left(\boldsymbol{e}_{s,p} - \boldsymbol{e}_{s,j}\right)^T \boldsymbol{C}_{L2E}(\widehat{\boldsymbol{u}}_2)\left(\left.\frac{\partial}{\partial\psi}\right|_{\hat{\theta},\hat{\varphi},\hat{\psi}} \boldsymbol{C}_{B2L}\right)\boldsymbol{b}_{12}^B$$

$$\left.\frac{\partial}{\partial\psi}\right|_{\hat{\theta},\hat{\varphi},\hat{\psi}} \boldsymbol{C}_{B2L} = \begin{bmatrix} -\sin\hat{\psi}\cos\hat{\varphi} & -\sin\hat{\psi}\sin\hat{\varphi}\sin\hat{\theta} - \cos\hat{\psi}\cos\hat{\theta} & -\sin\hat{\psi}\sin\hat{\varphi}\cos\hat{\theta} + \cos\hat{\psi}\sin\hat{\theta} \\ \cos\hat{\psi}\cos\hat{\varphi} & \cos\hat{\psi}\sin\hat{\varphi}\sin\hat{\theta} - \sin\hat{\psi}\cos\hat{\theta} & \cos\hat{\psi}\sin\hat{\varphi}\cos\hat{\theta} + \sin\hat{\psi}\sin\hat{\theta} \\ 0 & 0 & 0 \end{bmatrix}$$

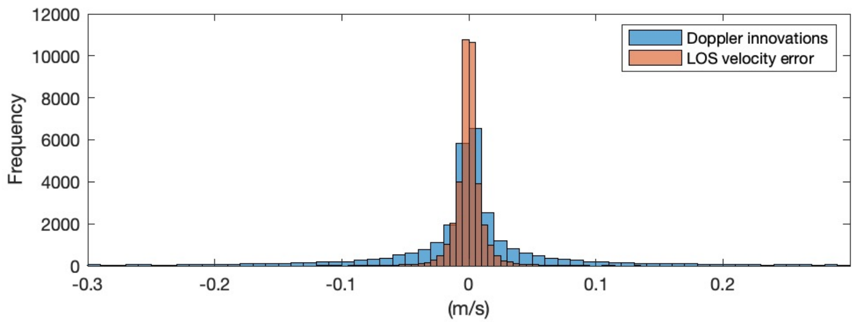
Multiple-receiver RTK

- Measurement model for pseudorange rate:

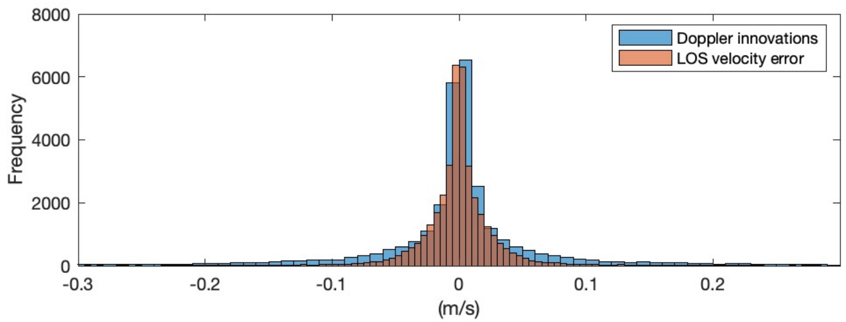
$$\boldsymbol{h}_{\dot{\rho}_2}(\boldsymbol{x})_{[i]} = (\dot{\boldsymbol{s}}_i - \dot{\boldsymbol{u}}_2)^T \boldsymbol{e}_i + c\delta\dot{t}_{u_2} + c\delta\dot{t}_{IF,i} + c\delta\dot{t}_{IS,i}$$

- Different velocities between receivers due to lever arm: $\dot{\boldsymbol{u}}_2^E = \dot{\boldsymbol{u}}_1^E + \boldsymbol{C}_{L2E}\boldsymbol{C}_{B2E}\|\boldsymbol{b}_{12}\| \begin{bmatrix} 0 \\ \omega_z \\ \omega_y \end{bmatrix}$

- Error from considering equal velocities vs Doppler innovations:



20 cm separation



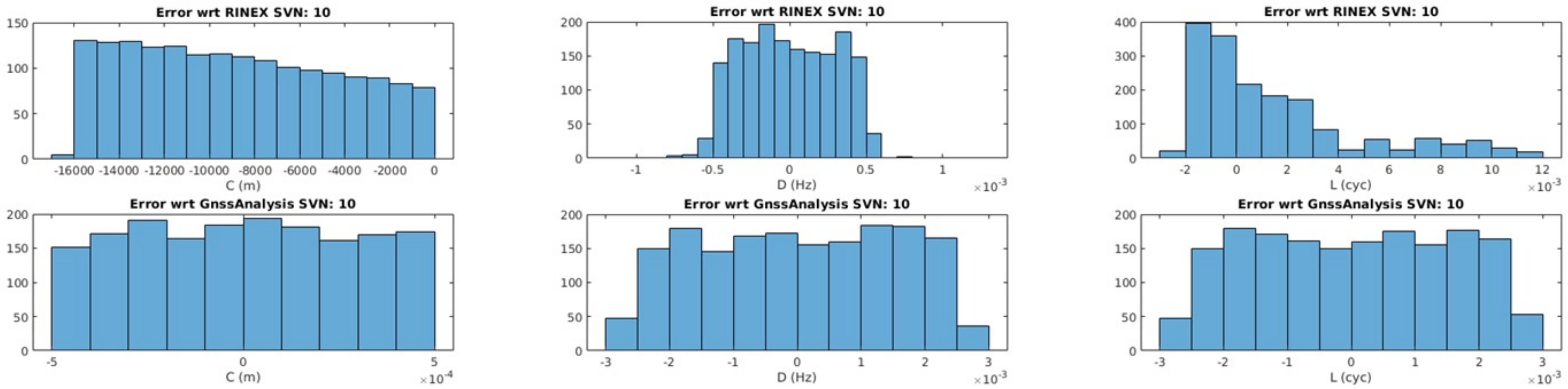
50 cm separation

➢ Noise model is inflated ⇨ All velocities are considered equal.

Measurement analysis

GnssLog vs RINEX

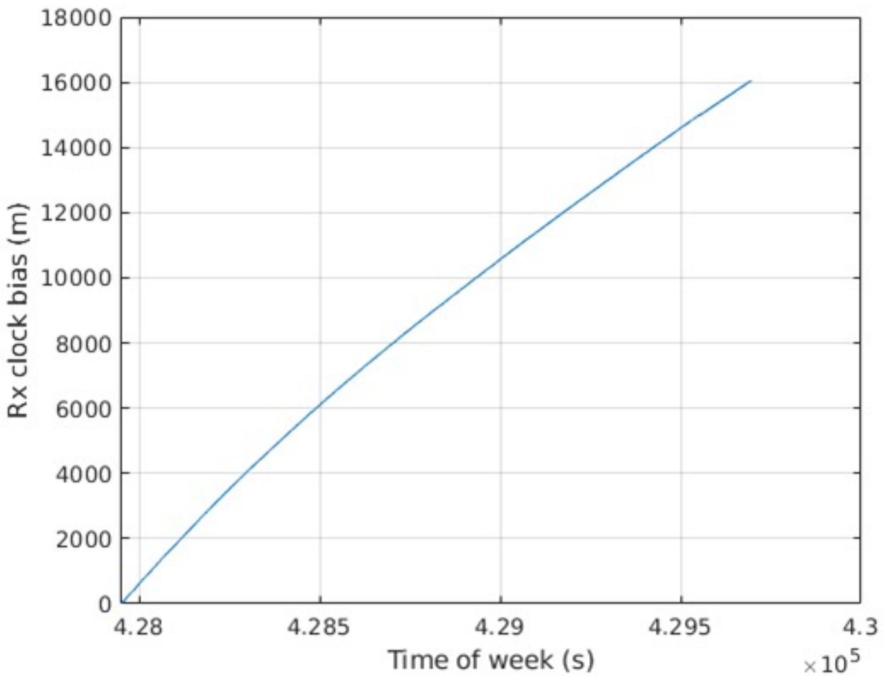
- GNSS observables from GnssLog compared to RINEX and GNSSAnalysis:

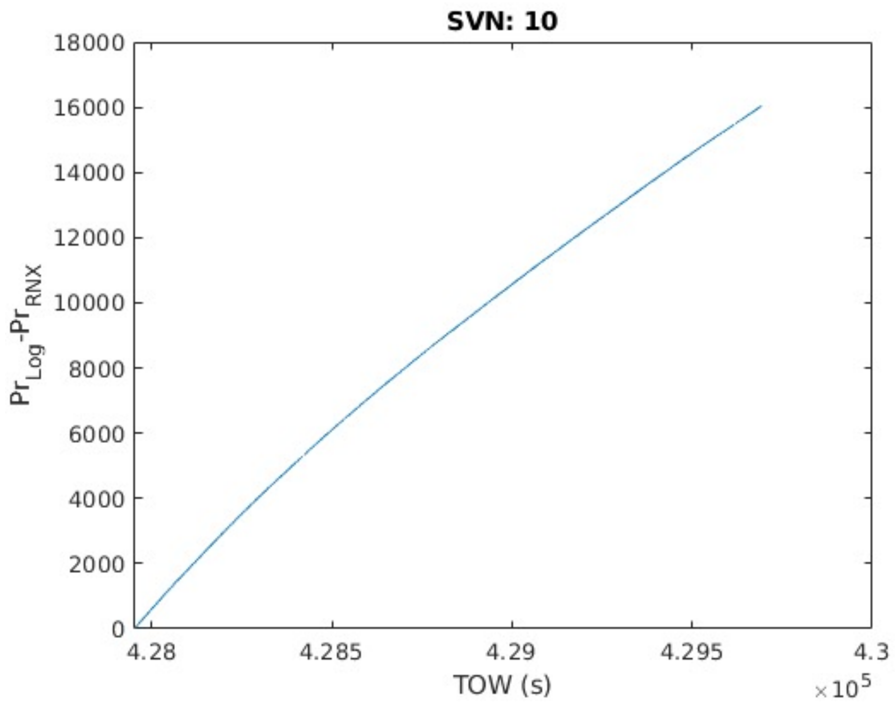


➢ RINEX pseudoranges strongly differ from GnssLog’s and GNSSAnalysis’s.

GnssLog vs RINEX

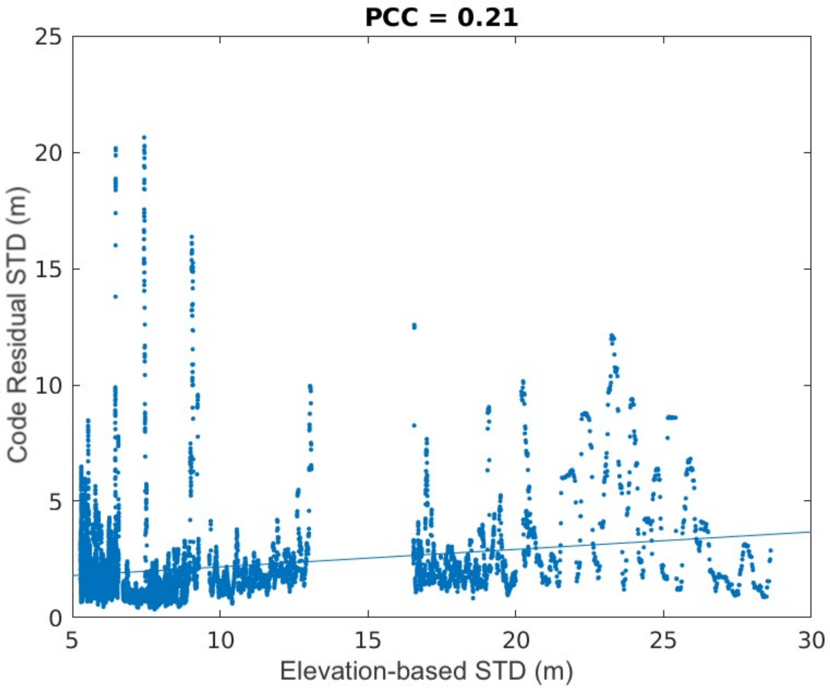
- Provided RINEX pseudoranges are corrected by receiver clock:



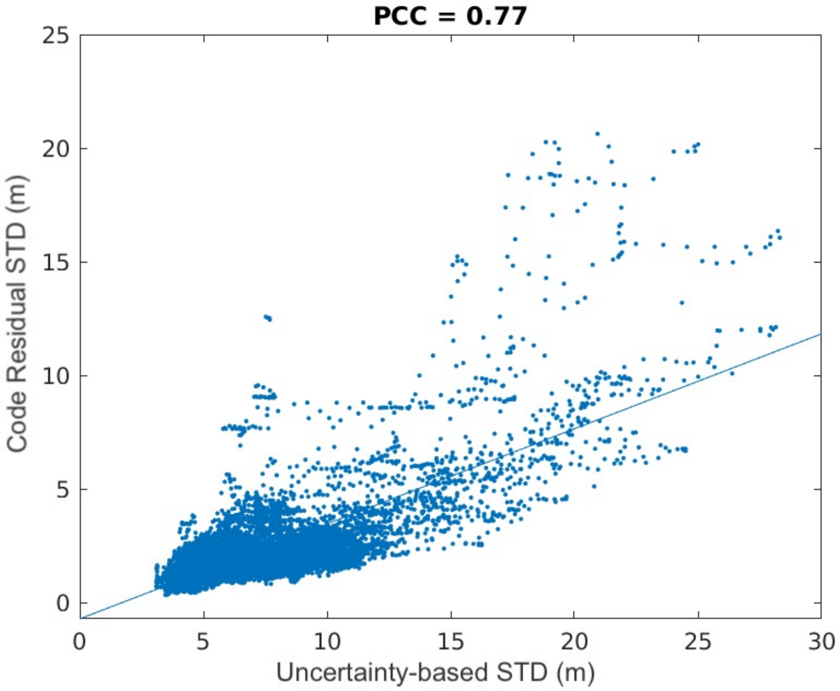


➢ Pseudorange measurements are corrected by clock bias in RINEX.

Reliability of measurement uncertainties



$$\hat{\sigma}_{\rho,i} = \frac{3}{\sin el}$$

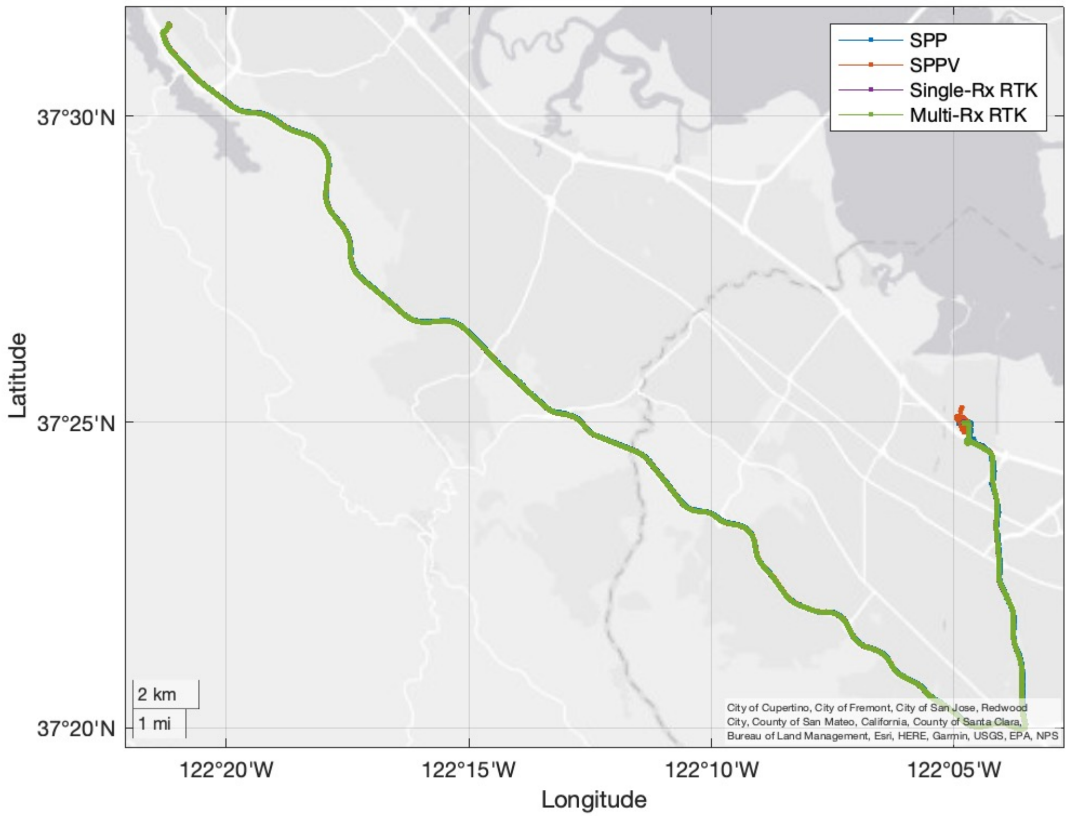


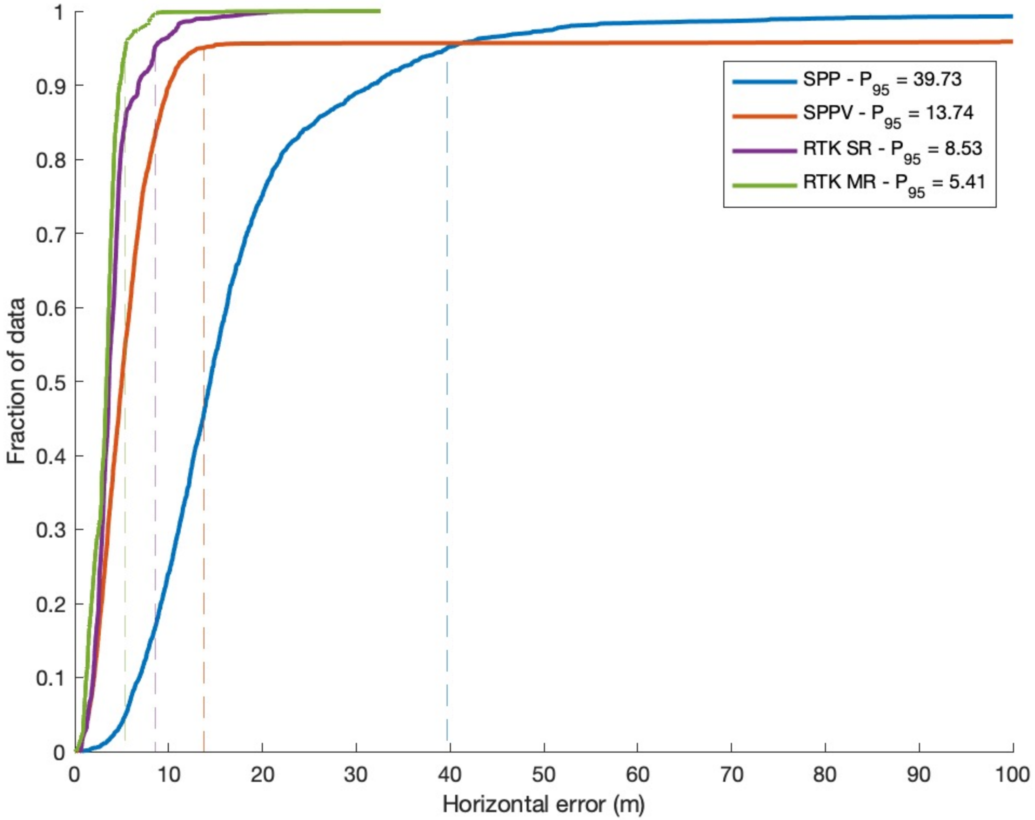
$$\hat{\sigma}_{\rho,i} = \sqrt{\sigma_{t_{clock}}^2 + \sigma_{t_{bias}}^2 + \sigma_{t_{tx}}^2}$$

➢ Uncertainty from *GnssLog* provides better estimation of covariance.

Results

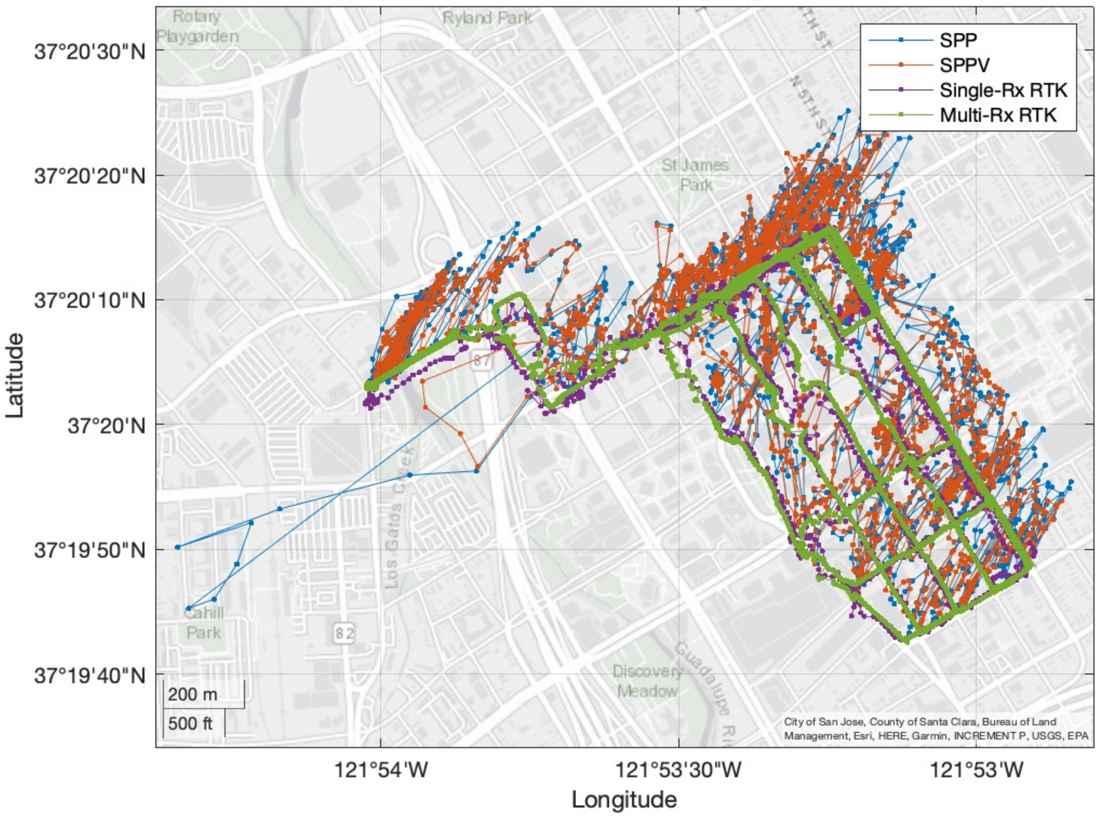
Comparison between positioning methods

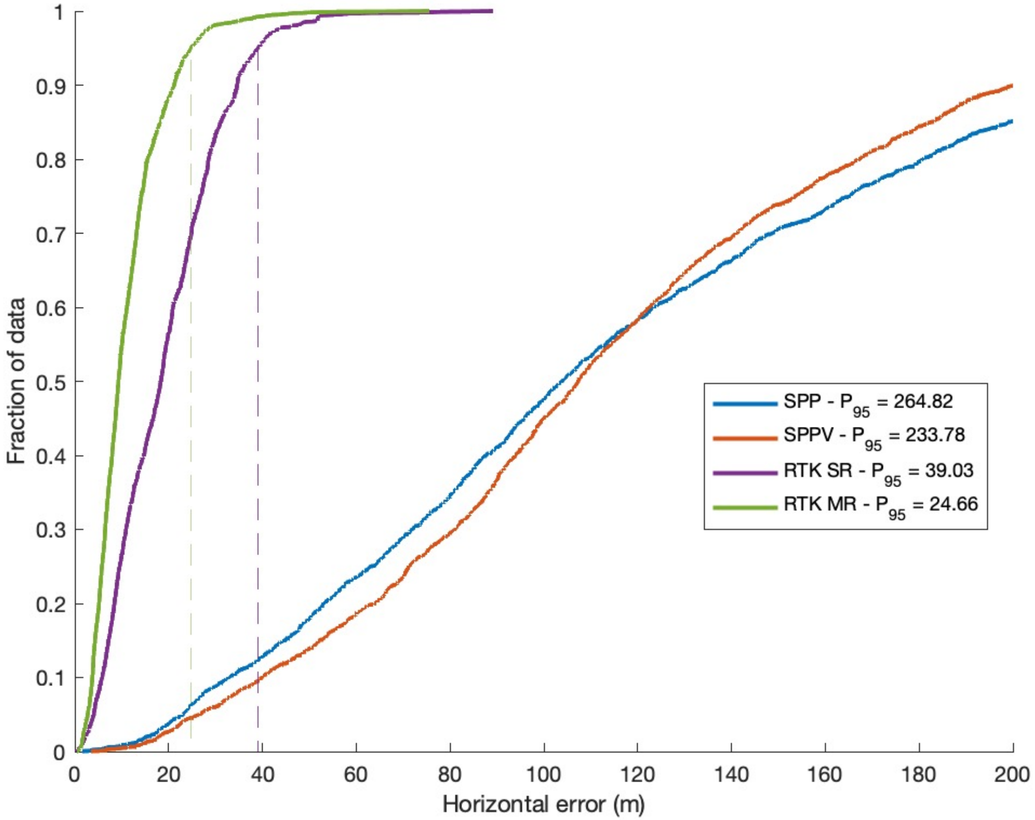




2020-05-29-US-MTV-1

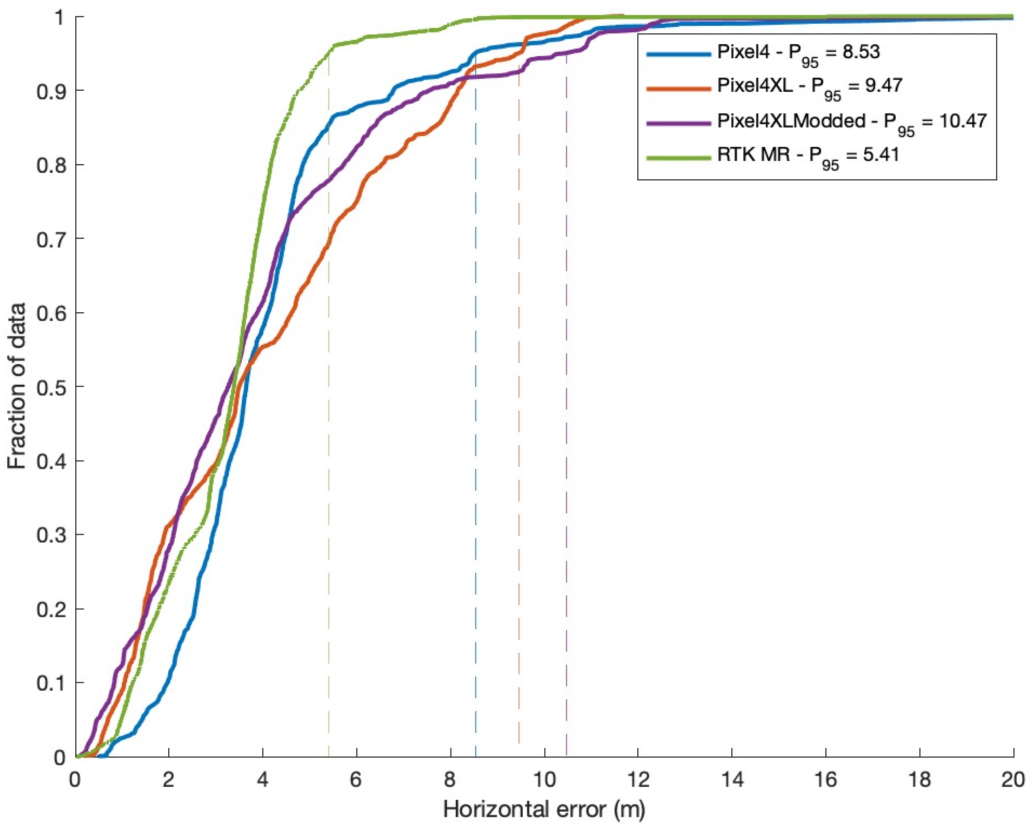
Comparison between positioning methods



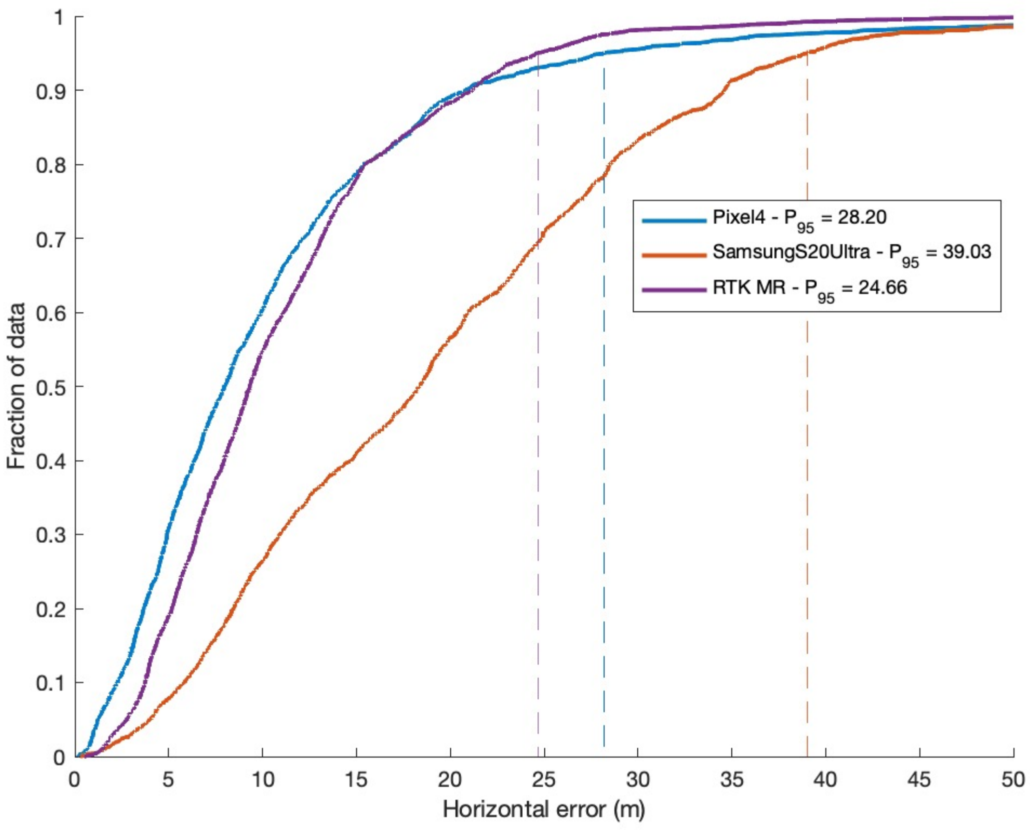


2021-04-28-US-SJC-1

Accuracy of multi-receiver RTK

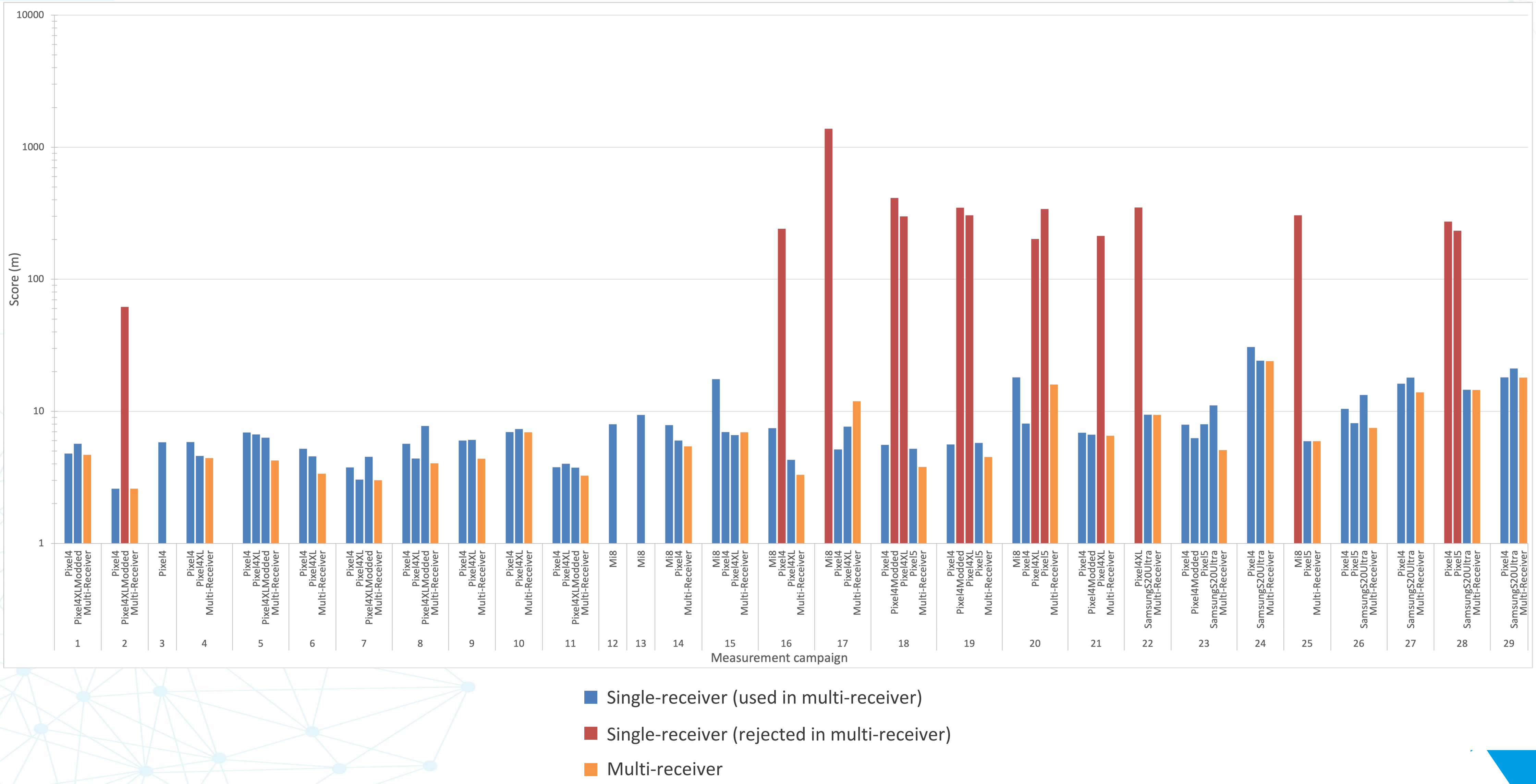


2020-05-29-US-MTV-1



2021-04-28-US-SJC-1

Results on the train dataset



Conclusions

Conclusions

- Use of Doppler shift improves accuracy, specially in highway scenarios.
- RTK can improve accuracy in smartphones.
- Multiple-receiver RTK with known geometry:
  - Improves accuracy with respect to single-receiver RTK.
  - Provides attitude estimation → Possible use for calibration of INS.

Future work

- Further research on Android GNSS raw measurements, especially carrier phase.
- Include integer ambiguity resolution (LAMBDA) and dedicated cycle-slip detection method.
- Use of non-diagonal measurement covariance matrix with sequential KF.
- Weighting of smartphones in multiple-receiver RTK.
- Inter-smartphone clock bias estimation.
- Hybridization with INS.