THE HONG KONG POLYTECHNIC UNIVERSITY
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Session C6: Harsh Urban and Indoor GNSS

Open-Source GNSS Direct Position Estimation Plug-in Module for Two-Step Positioning SDRs

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Background – Current problem

Problem with GNSS in urban environments?

- Multipath (MP) and non-line-of-sight (NLOS) receptions, attenuation, and diffraction from urban structures.

Common Mitigation methods?

- Integration with other systems, including but not limited to 3D mapping, and inertial navigation systems (INS).
- But such methods relied on other positioning systems and does not improve the performance of sole GNSS receivers

Zhang, G., & Hsu, L. T. (2021). Performance assessment of GNSS diffraction models in urban areas. NAVIGATION, 68(2), 369-389. https://doi.org/10.1002/navi.417

Wen, W., Bai, X., Kan, Y. C., & Hsu, L.-T. (2019). Tightly Coupled GNSS/INS Integration via Factor Graph and Aided by Fish-Eye Camera. IEEE Transactions on Vehicular Technology, 68(11), 10651-10662. https://doi.org/10.1109/tvt.2019.2944680

Background – Two-step positioning (2SP) receivers

Scalar Tracking Loop (STL) – Non-linear Least Square (LS) Estimator

- Independent tracking loops estimate pseudorange and pseudorange rates of individual satellites
- No information sharing between tracking loops
- No information fed back from navigation processor (LS)

Vector Tracking Loop (VTL) – Extended Kalman Filter (EKF)

- Code discriminator and carrier loop filter outputs are fed towards the EKF
- PVT are fed back into tracking loops to aid in estimating the code phase and carrier frequency => mutual aiding

Lashley, M., Bevly, D. M., & Hung, J. Y. (2010). A valid comparison of vector and scalar tracking loops. IEEE/ION Position, Location and Navigation Symposium, Indian Wells, CA, USA.

Xu, B., Jia, Q., & Hsu, L.-T. (2020). Vector Tracking Loop-Based GNSS NLOS Detection and Correction: Algorithm Design and Performance Analysis. IEEE Transactions on Instrumentation and Measurement, 69(7), 4604-4619. https://doi.org/10.1109/tim.2019.2950578

Direct Position Estimation (DPE)

- A single-step positioning algorithm
- Skips intermediate measurements i.e., code delay and Doppler freq.
- **Directly** calculates the positioning estimates in the navigation domain

Two-step receivers

Baseband signal → Acquisition and Tracking → (1) Estimation of intermediate parameters i.e., pseudorange and pseudorange rate → (2) Positioning with non-linear Least Squares

Direct Position Estimation

Baseband signal → Acquisition → (1) Positioning in the navigation domain

Closas, P., Fernandez-Prades, C., & Fernandez-Rubio, J. A. (2007). Maximum Likelihood Estimation of Position in GNSS. IEEE Signal Processing Letters, 14(5), 359-362. https://doi.org/10.1109/lsp.2006.888360

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Background – Direct Position Estimation

Main idea:

- Satellite signals code delay and Doppler frequencies are functions of the receiver's position, velocity, and time (PVT), $\boldsymbol{\gamma} = [\mathbf{p}^{\mathrm{T}}, \delta\mathrm{t}]^{\mathrm{T}}$

- A specific value of PVT corresponds to a specific code delay and Doppler frequency, value $f_d(\boldsymbol{\gamma})$ and $\tau(\boldsymbol{\gamma})$

Received baseband signal vector

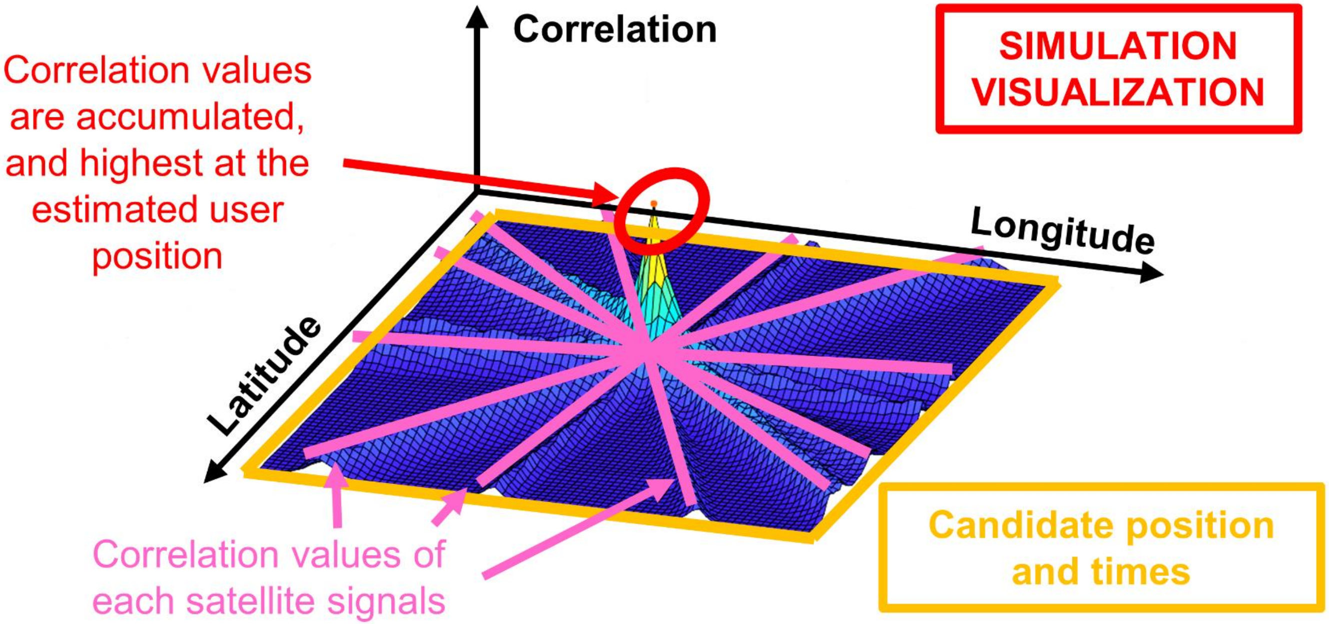
Signal replica for PRN *i*, generated as a function of the PVT

$$\hat{\boldsymbol{\gamma}} = \arg\max_{\boldsymbol{\gamma}} \{\textstyle\sum_{i=1}^{M} \|\mathbf{x}^{\mathrm{H}} \boxed{\mathbf{c}_i(\boldsymbol{\gamma})}\|^2\}$$

Closas, P., & Gao, G. (2020). Direct Position Estimation. *Position, Navigation, and Timing Technologies in the 21st Century: Integrated Satellite Navigation, Sensor Systems, and Civil Applications*, *1*, 529-550.

Background – Direct Position Estimation

Local signal replicas are for each candidate PVT, and correlated with the incoming signal



Vicenzo S, Xu B, Xu H, Hsu L-T (2024) GNSS direct position estimation-inspired positioning with pseudorange correlogram for urban navigation. GPS Solutions 28(2). https://doi.org/10.1007/s10291-024-01627-5

Background – Direct Position Estimation

Proven to offer **superior performance against 2SP**

How?

- Weak signal reception
- MP reception

Proven through…

- Theoretical bounds i.e., Cramér-Rao lower bound (CRLB) and Ziv-Zakai bound (ZZB)
- Statistical multipath channel models (DLR)

Closas, P., Fernández-Prades, C., & Fernández-Rubio, J. A. (2009a). Cramér–Rao Bound Analysis of Positioning Approaches in GNSS Receivers. IEEE Transactions on Signal Processing, 57(10), 3775-3786. https://doi.org/10.1109/TSP.2009.2025083

Closas, P., Fernández-Prades, C., Fernández, A., Wis, M., Vecchione, G., Zanier, F., Garcia-Molina, J., & Crisci, M. (2015). Evaluation of GNSS direct position estimation in realistic multipath channels. 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2015)

Gusi-Amigó, A., Closas, P., Mallat, A., & Vandendorpe, L. (2018). Ziv-Zakai Bound for Direct Position Estimation. NAVIGATION, 65(3), 463-475. https://doi.org/10.1002/navi.259

Problem Statement

GNSS positioning with DPE is mostly **left uninvestigated** and **unapplied commercially**.

Why???

Difficult practical implementation

To that end…

we propose our own open-source DPE implementation.

Objective:

1. Spur research into DPE as a more robust positioning technique compared to 2SP.

2. Better understanding and familiarity of a practical implementation of DPE.

Dampf, J., Frankl, K., & Pany, T. (2018). Optimal Particle Filter Weight for Bayesian Direct Position Estimation in a GNSS Receiver. Sensors, 18(8), 2736. https://doi.org/10.3390/s18082736

Objective

- So far only Peretic and Gao (2021) have previously open-sourced their DPE software, programmed in Python and C++.

- Unlike Peretic and Gao (2021), we propose our DPE as a plug-in module that can be easily integrated into any open-sourced 2SP MATLAB SDRs.

- Allows for easier understanding and ease-of-use for people unfamiliar with DPE

Peretic, M., & Gao, G. X. (2021). Design of a parallelized direct position estimation-based GNSS receiver. NAVIGATION, 68(1), 21-39. https://doi.org/10.1002/navi.402

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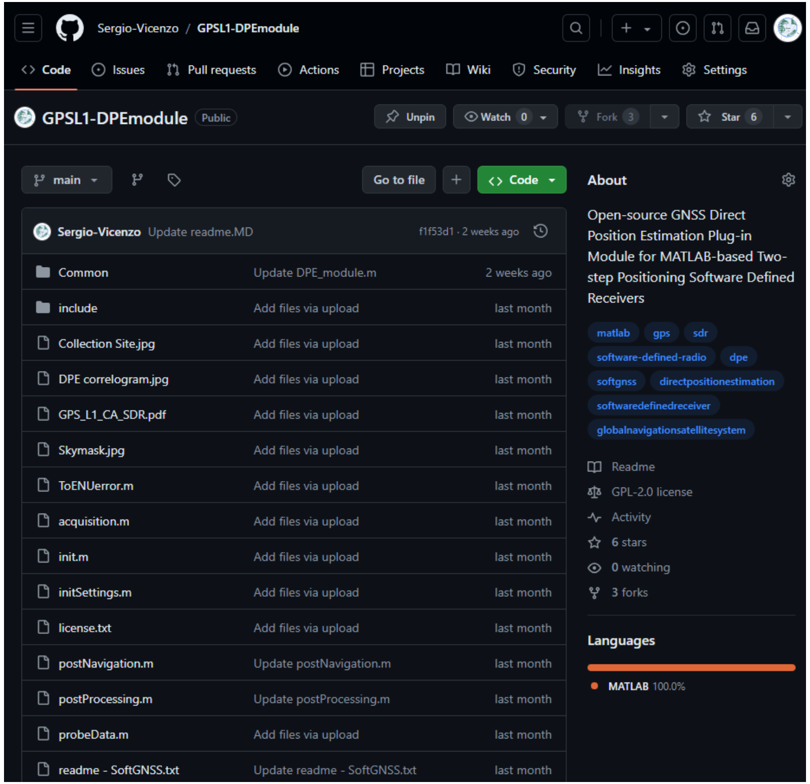
Our Proposed DPE module – Available at GitHub

The code is now available at **GitHub**



https://github.com/Sergio-Vicenzo/GPSL1-DPEmodule

Borre, K., Akos, D. M., Bertelsen, N., Rinder, P., & Jensen, S. H. (2007). A software-defined GPS and galileo receiver: A single-frequency approach.

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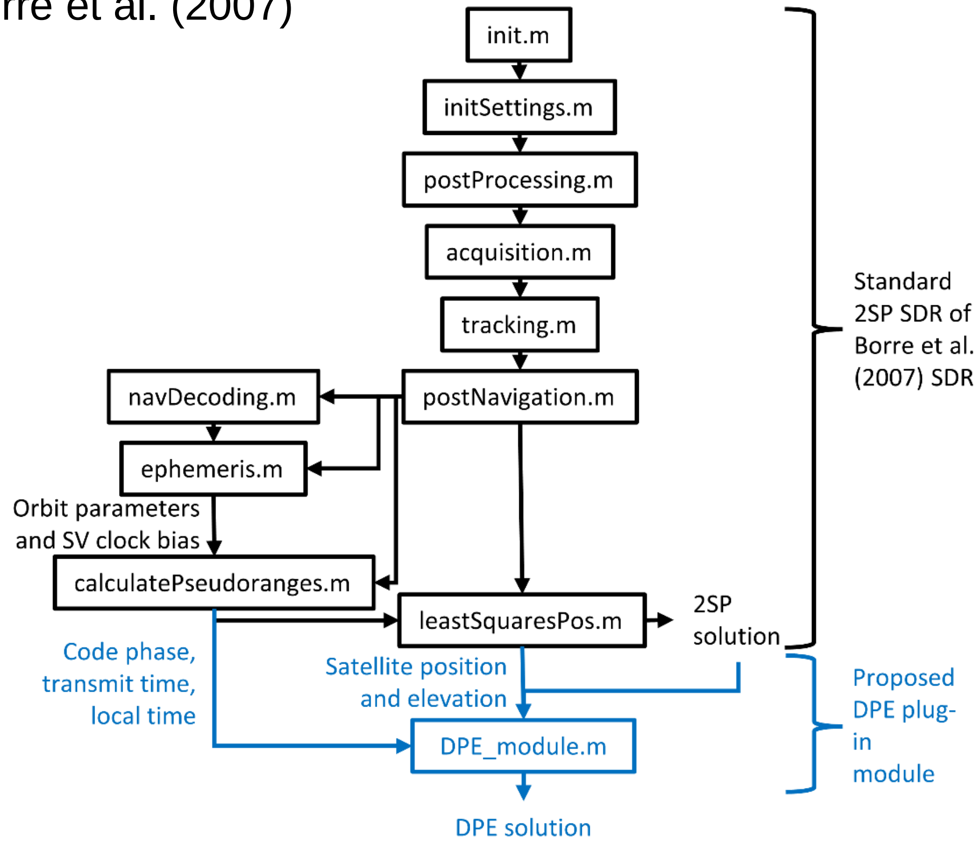
Methodology – Our Proposed DPE module

Integrated with the GPS L1 C/A **SoftGNSS v3.0** MATLAB 2SP Scalar Tracking Loop (STL) SDR by Borre et al. (2007)



Borre, K., Akos, D. M., Bertelsen, N., Rinder, P., & Jensen, S. H. (2007). A software-defined GPS and galileo receiver: A single-frequency approach.

Peretic, M. (2019). Development and analysis of a parallelized direct position estimation-based GPS receiver implementation (Doctoral dissertation, University of Illinois at Urbana-Champaign).

Closas, P., Fernández-Prades, C., Fernández, A., Wis, M., Vecchione, G., Zanier, F., & Crisci, M. (2015, September). Evaluation of GNSS direct position estimation in realistic multipath channels. In Proceedings of the 28th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2015) (pp. 3693-3701).

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Methodology – Our Proposed DPE module

- **DPE cost function**

$$\hat{\boldsymbol{\gamma}} = \arg\max_{\boldsymbol{\gamma}} \sum_{i=1}^{M} \sum_{j=1}^{J} \left\| \mathbf{x}^{H} \mathbf{c}_i(\boldsymbol{\gamma}_j) \right\|^2$$

- **Received baseband signal**

Code freq. Code phase Carrier freq. Carrier phase

$$\mathrm{x}(n) = \sum_{i=1}^{M} a^i s^i \{ (f_{C/A} + \boxed{f^i_{\mathrm{code,t}}}) n + \boxed{\varphi^i_{\mathrm{code,t}}} \} \exp\{ j2\pi (f_{\mathrm{L1}} + \boxed{f^i_{\mathrm{carr,t}}}) n + \boxed{\varphi^i_{\mathrm{carr,t}}} \}$$

- **Replica signal for each candidate PVT**

$$\mathrm{c}_i(\boldsymbol{\gamma}_j, n) = s^i \{ (f_{C/A} + \boxed{f^i_{\mathrm{code,t}}}) n + \boxed{\varphi^i_{\mathrm{code,t}}} + \boxed{\Delta\varphi^i_{\boldsymbol{\gamma}_j}} \} \exp\{ j2\pi (f_{\mathrm{L1}} + \boxed{f^i_{\mathrm{carr,t}}}) n + \boxed{\varphi^i_{\mathrm{carr,t}}} \}$$

Difference in code phase between candidate PVT and estimated code phase at time *t*

- **where…**

Local time Transmission time

$$\Delta\varphi^i_{\boldsymbol{\gamma}_j} = f_{\mathrm{C/A}} (\boxed{t} - \boxed{t^i_{\mathrm{transmit}}}) - \frac{f_{\mathrm{C/A}}}{c} \left(\left\| \mathbf{p}^{\mathrm{i}} - \mathbf{p}_j \right\| + (\delta t_j - \delta t^i) \cdot c + I + T \right)$$

Peretic, M., & Gao, G. X. (2021). Design of a parallelized direct position estimation-based GNSS receiver. NAVIGATION, 68(1), 21-39. https://doi.org/10.1002/navi.402

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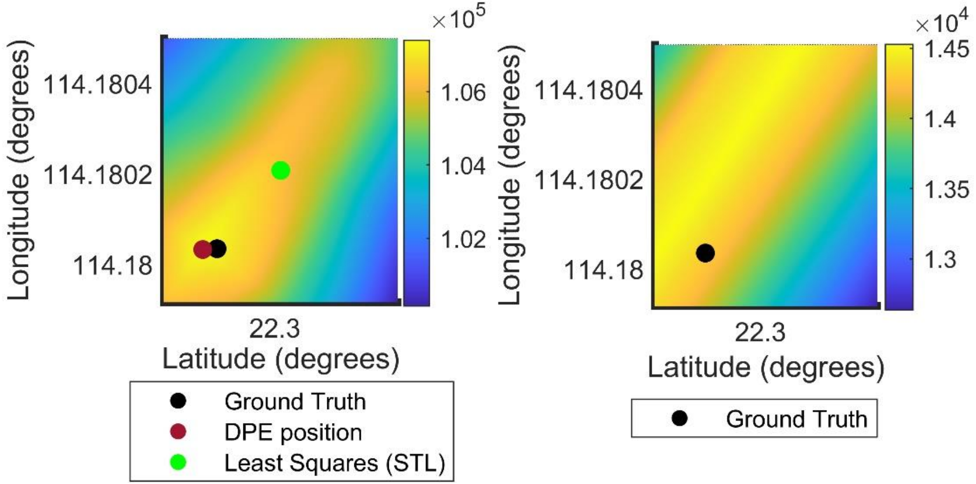
Methodology – Our Proposed DPE module

- **Pre-calculate the correlations** per every pre-determined chip spacing or code phase.
- The correlations for every candidate PVT would later be given based on its code phase.
- Since it is virtually impossible to pre-calculate the correlations that would fit perfectly to every candidate PVT code phase, the correlations would be interpolated.



Axelrad, P., Donna, J., & Mitchell, M. (2009, September). Enhancing GNSS acquisition by combining signals from multiple channels and satellites. In Proceedings of the 22nd International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2009) (pp. 2617-2628).

Cheong, J. W., Wu, J., Dempster, A. G., & Rizos, C. (2011, November). Efficient implementation of collective detection. In *IGNSS symposium* (Vol. 170).

Methodology – Data Collection Method

Evaluation of the proposed DPE module will use both real and simulated static GNSS data.

Front-end	NI USRP N210	NI USRP B210	NSL Stereo	LABSAT 3W (For SPIRENT simulation)
Sampling Frequency	10 MHz	20 MHz	26 MHz	58 MHz
Bandwidth	10 MHz	2 MHz	8 MHz	56 MHz
Antenna	ZYACF-L004		Allystar AGR6303	-

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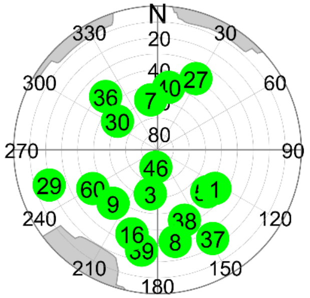
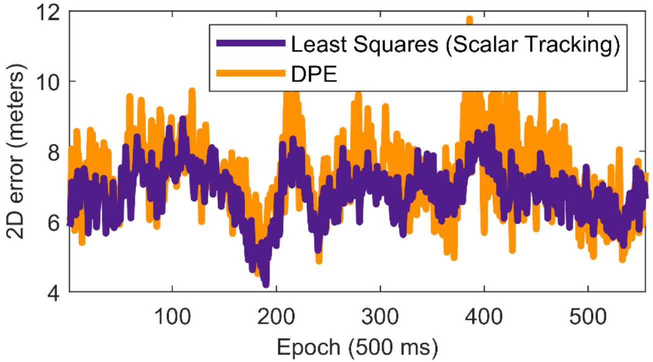
Results – Open sky scenario

- BeiDou B1I



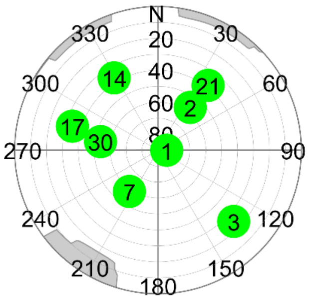


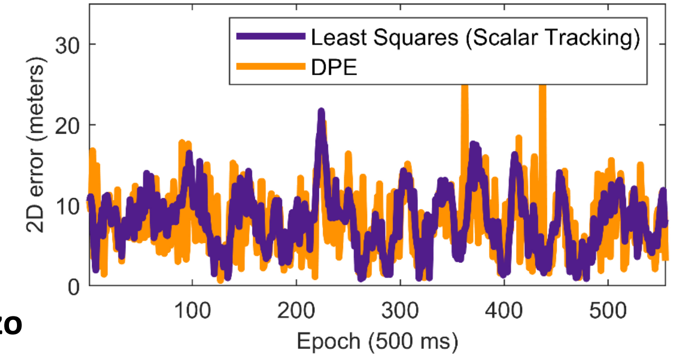
Comparable performance in open sky conditions

2SP 2D Mean Error	DPE 2D Mean Error
6.85 meters	7.25 meters

Closas, P., & Gusi-Amigo, A. (2017). Direct position estimation of GNSS receivers: Analyzing main results, architectures, enhancements, and challenges. IEEE Signal Processing Magazine, 34(5), 72-84.

- GPS L1 C/A



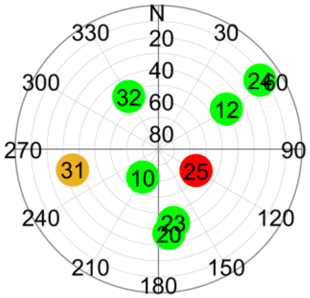


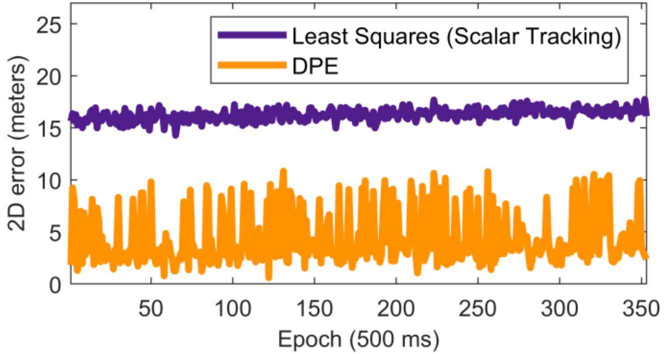
2SP 2D Mean Error	DPE 2D Mean Error
8.11 meters	7.71 meters

Results – SPIRENT simulated urban scenarios

DPE outperforms 2SP in simulated urban data

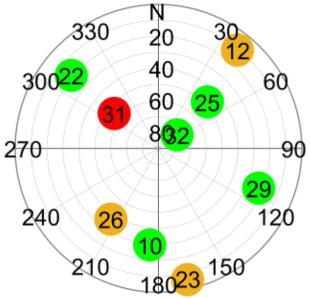
- Light Urban (1 MP, 1 NLOS) – GPS L1 C/A

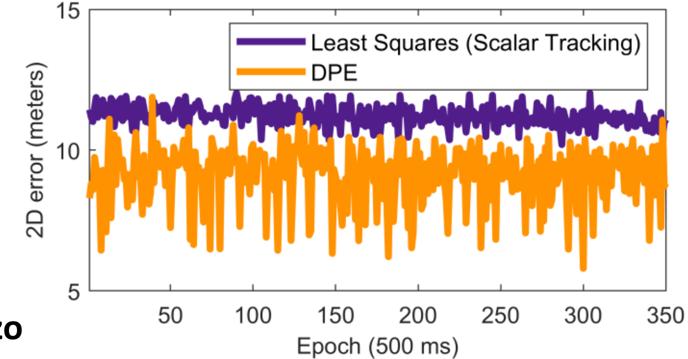




2SP 2D Mean Error	DPE 2D Mean Error
16.26 meters	**4.29** meters

- Medium Urban (3 MP, 1 NLOS) – GPS L1 C/A





2SP 2D Mean Error	DPE 2D Mean Error
11.22 meters	**9.13** meters

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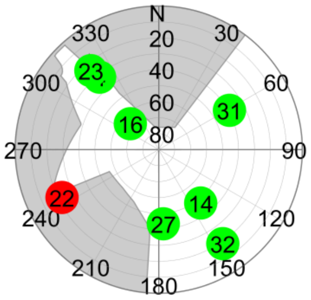
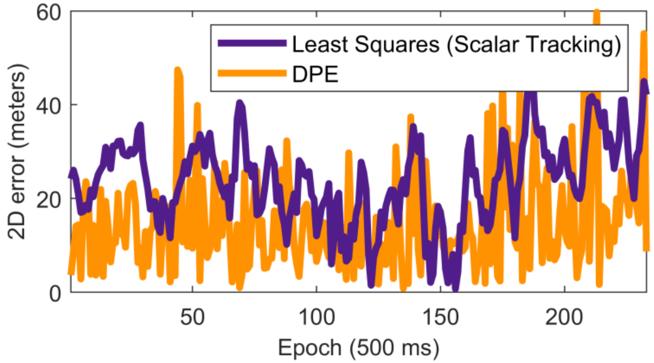
Results – NLOS scenarios

- East Tsim Sha Tsui (Urban) – GPS L1 C/A

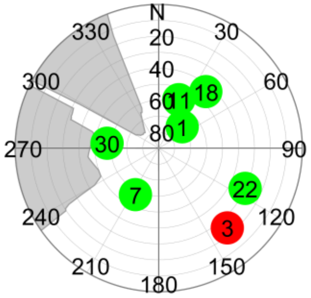
Xu, B., Jia, Q., & Hsu, L.-T. (2020). Vector Tracking Loop-Based GNSS NLOS Detection and Correction: Algorithm Design and Performance Analysis. IEEE Transactions on Instrumentation and Measurement, 69(7), 4604-4619. https://doi.org/10.1109/tim.2019.2950578

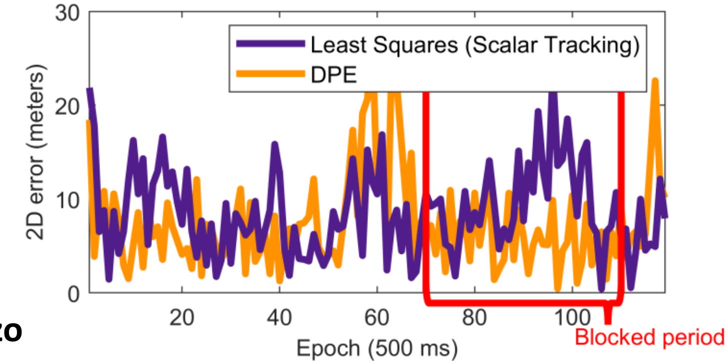




2SP 2D Mean Error	DPE 2D Mean Error
23.82 meters	**14.92** meters

- Whampoa promenade (Light Urban) – GPS L1 C/A





Errors during blocked period

2SP 2D Mean Error	DPE 2D Mean Error
9.76 meters	**6.42** meters

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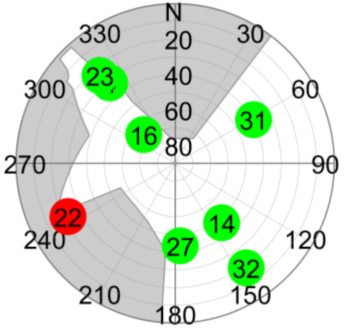
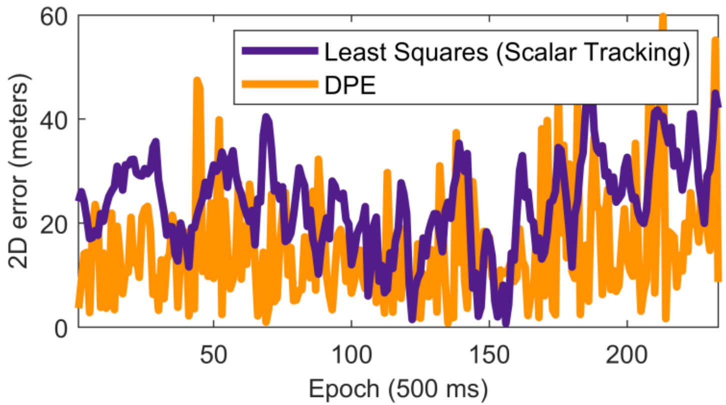
Results – Digging deeper into NLOS scenarios

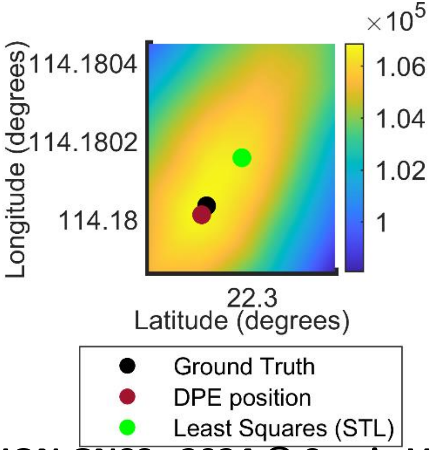
East Tsim Sha Tsui



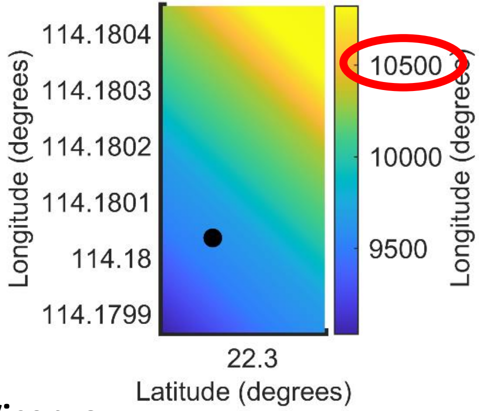


DPE has strong resilience against NLOS reception

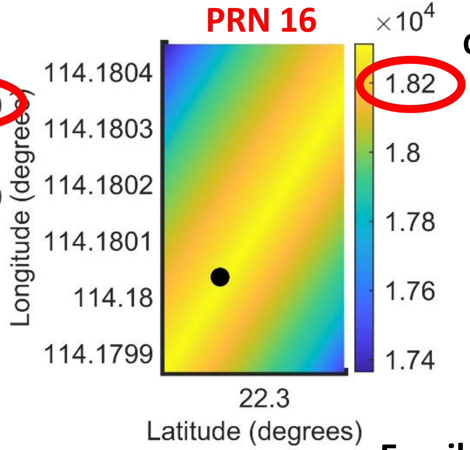
2SP 2D Mean Error	DPE 2D Mean Error
23.82 meters	**14.92 meters**



PRN 22 (NLOS)



PRN 16



Correlations of an NLOS satellite (PRN 22)

1. Deviate from the ground truth

2. Much weaker compared to that of the highly elevated (PRN 16)

Thus, NLOS satellite correlations do not contribute to the global maxima

i.e., NLOS measurement naturally excluded from PVT estimation

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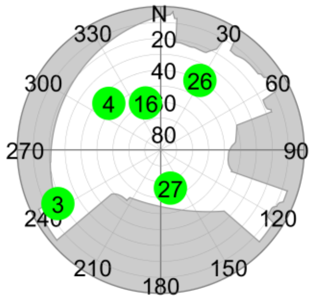
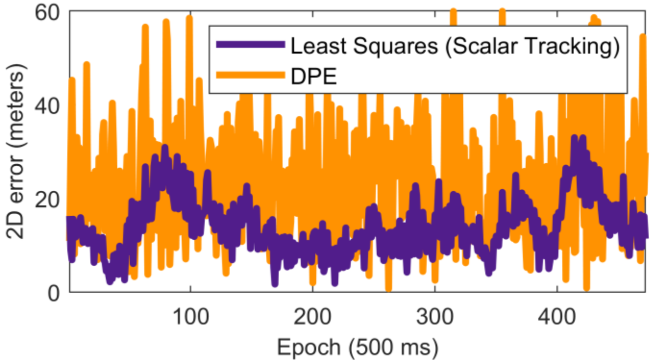
Results – Harsh Urban scenarios

- HK PolyU campus – GPS L1 C/A



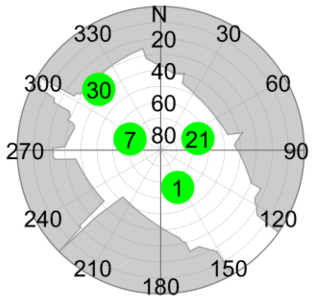


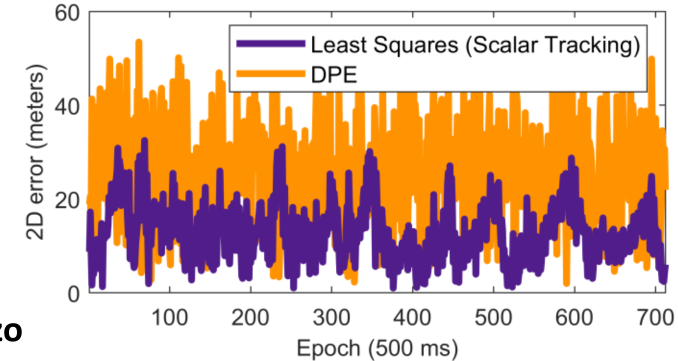
Further iterating DPE's issue of misspecified signal model!

2SP 2D Mean Error	DPE 2D Mean Error
14.03 meters	23.20 meters

Vicenzo, S., Xu, B., Dey, A., & Hsu, L.-T. (2023). Experimental Investigation of GNSS Direct Position Estimation in Densely Urban Area. 36th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2023), Denver, Colorado.

- East Tsim Sha Tsui – GPS L1 C/A





2SP 2D Mean Error	DPE 2D Mean Error
12.86 meters	25.20 meters

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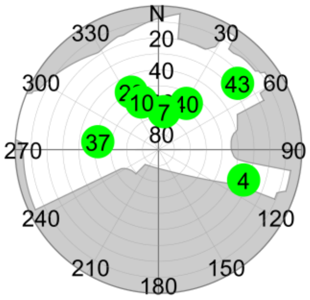
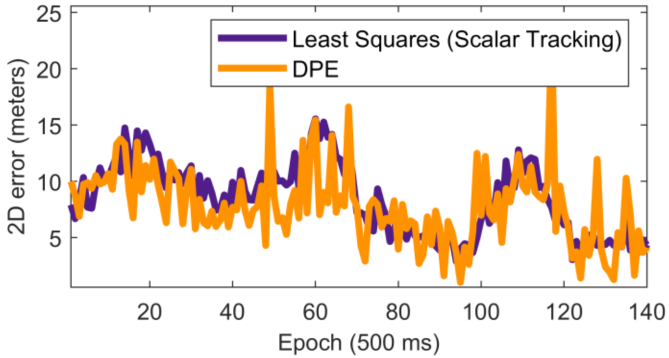
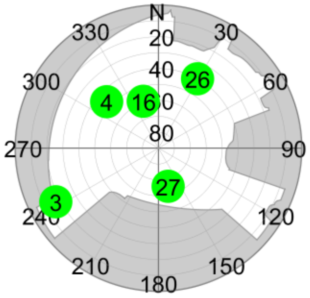
Results – BDS B1I vs GPS L1 C/A in the same harsh urban location

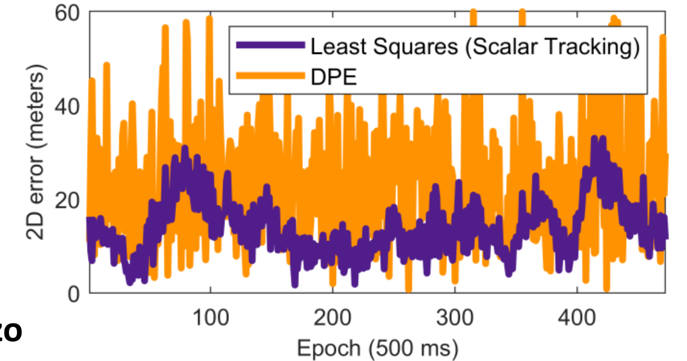
- HK PolyU campus – BeiDou B1I





- HK PolyU campus – GPS L1 C/A





DPE's issue of misspecified signal model *alleviated* with more satellite availability!

2SP 2D Mean Error	DPE 2D Mean Error
8.41 meters	7.83 meters

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2SP 2D Mean Error	DPE 2D Mean Error
14.03 meters	23.20 meters

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Conclusion

Proposed our novel implementation of a DPE receiver, which is now available at

https://github.com/Sergio-Vicenzo/GPSL1-DPEmodule

Aim:

Better familiarization and understanding of DPE,

and

promotion and popularization of DPE research and application

Advantages?

- Coded in an easy-to-learn language, MATLAB
- Integration not restricted to STL – VTL also possible
- Integration not restricted to GPS L1 C/A – Can be any BPSK modulated signals

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Conclusion

DPE has strong **resilience against NLOS** reception

But…

- Further reiterate DPE’s issue of misspecified signal model in urban environments

- The use of more satellites alleviates said issue since more LOS satellites are available

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Thank you!

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Google Scholar: https://scholar.google.com.hk/citations?user=MjNYX3kAAAAJ&hl=en

ResearchGate: https://www.researchgate.net/profile/Sergio_Vicenzo

ORCID: https://orcid.org/0000-0003-2974-7899

LinkedIn: http://www.linkedin.com/in/sergio-vicenzo/

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Axelrad, P., Donna, J., & Mitchell, M. (2009, September). Enhancing GNSS acquisition by combining signals from multiple channels and satellites. In Proceedings of the 22nd International Technical Meeting of The Satellite Division of the Institute of Navigation (ION GNSS 2009) (pp. 2617-2628).

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