

Empirical Analysis of Multipath and Non-Line-of-Sight Errors on Receiver Measurements in an Urban Environment

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September 12, 2025

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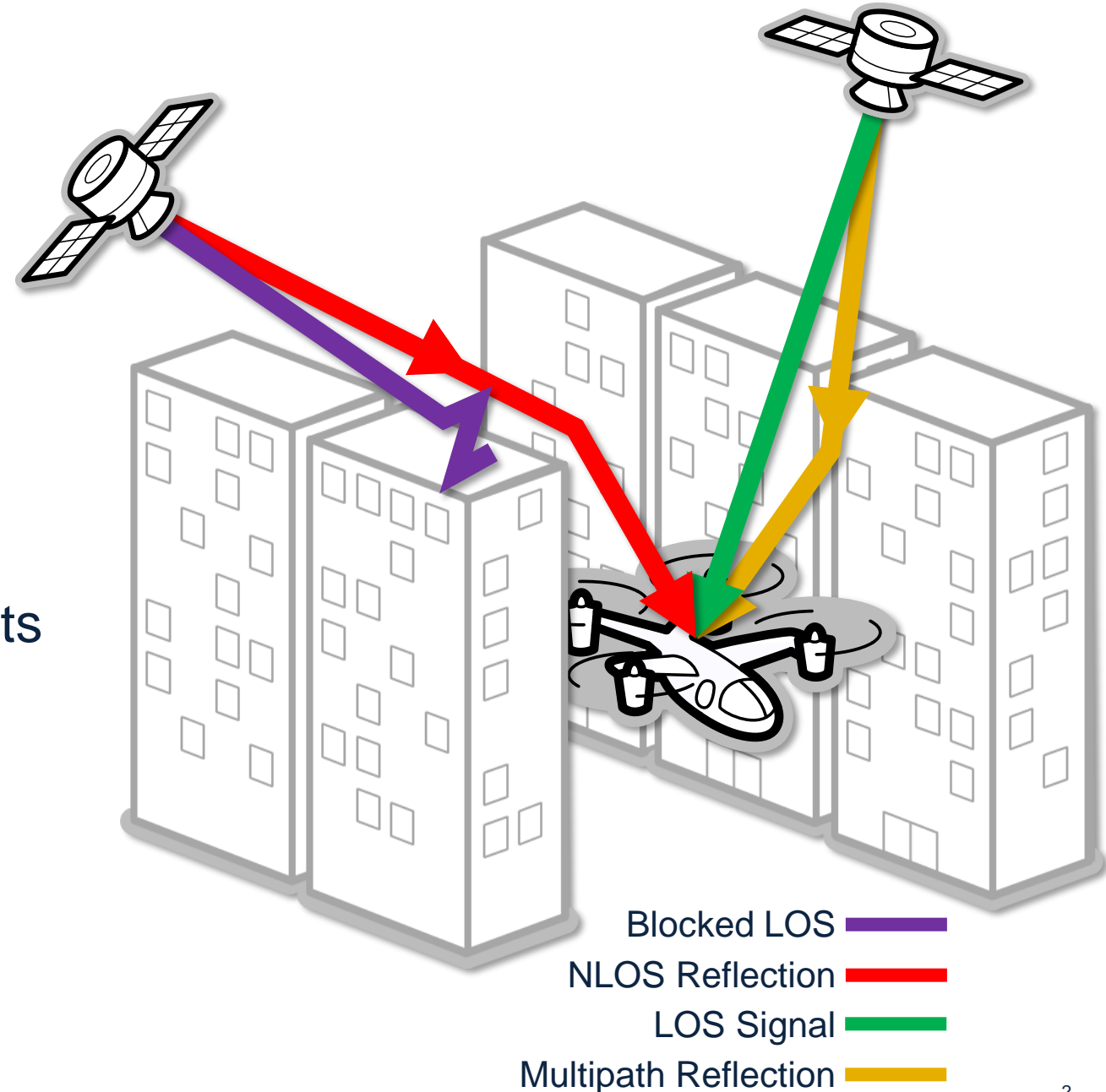
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Introduction

- Urban canyons can be challenging for GNSS-based navigation
 - Buildings can block the LOS to satellites and reflect NLOS signals
 - Multiple reflections can interfere with each other (known as multipath)
- Pseudorange errors from urban effects are more than “lengthened paths”...
 - Position- and time-varying
 - Change by meters from centimeters of receiver movement
 - Can be negative



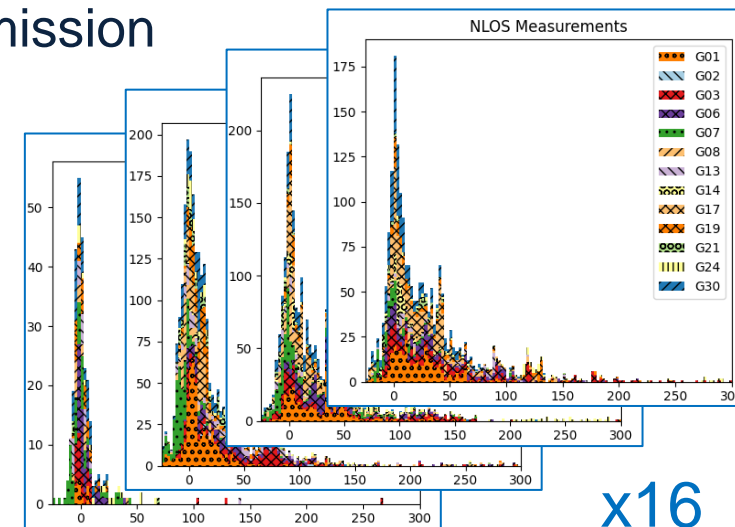
Background

Motivation: urban navigation risk assessment

- Better understand urban pseudorange error behaviors to:
 - Extend rigorous GNSS integrity concepts [1, 2]
 - Assess if a navigation technique is resilient and robust to the urban effects expected in a proposed mission
- Prior work
 - Our prior work: *Statistical Analysis of GNSS Multipath Errors in Urban Canyons* (ION PLANS 2025) [3]
 - Other prior empirical studies: [4, 5, 6]

Are the error distributions:

- Symmetric or asymmetric?
- Where's the mass?
- How long are the tails?




Pseudorange error distributions as a function of urban canyon shape [3]

This work: **statistical** findings from **empirical** data of the impact of these effects on pseudorange measurements

Multipath Error Isolation

Data Inputs


RINEX .obs logs
of two "test receivers"


Reference station
with RINEX .obs logs


Truth positions
of "test receivers"


Urban digital
elevation map

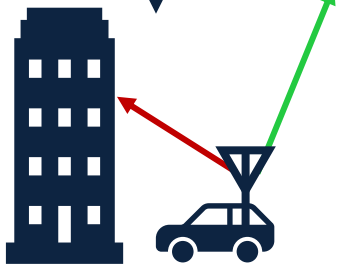
Processing

Three steps:
1. Subtract known true range from measurements
2. Single-difference measurements with reference station
3. Estimate and remove clock bias


Assess if the LOS is
blocked for each satellite
at each truth position [7, 8]

Data Outputs


Pseudorange **Errors**
due to **Multipath** Interference
and **NLOS** Reception


Measurements
Classified Either
LOS or **NLOS**


Canyon **Depth**
Classifications

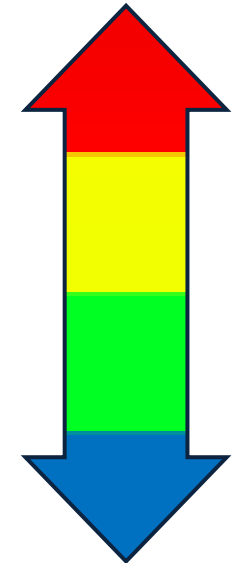

Canyon "Sided-ness"
Classifications

Dataset Overview

Discrete colors and icon shapes are consistent with prior work ([4])



Deepest canyon
(Tallest buildings)



Shallowest canyon
(Lowest buildings)

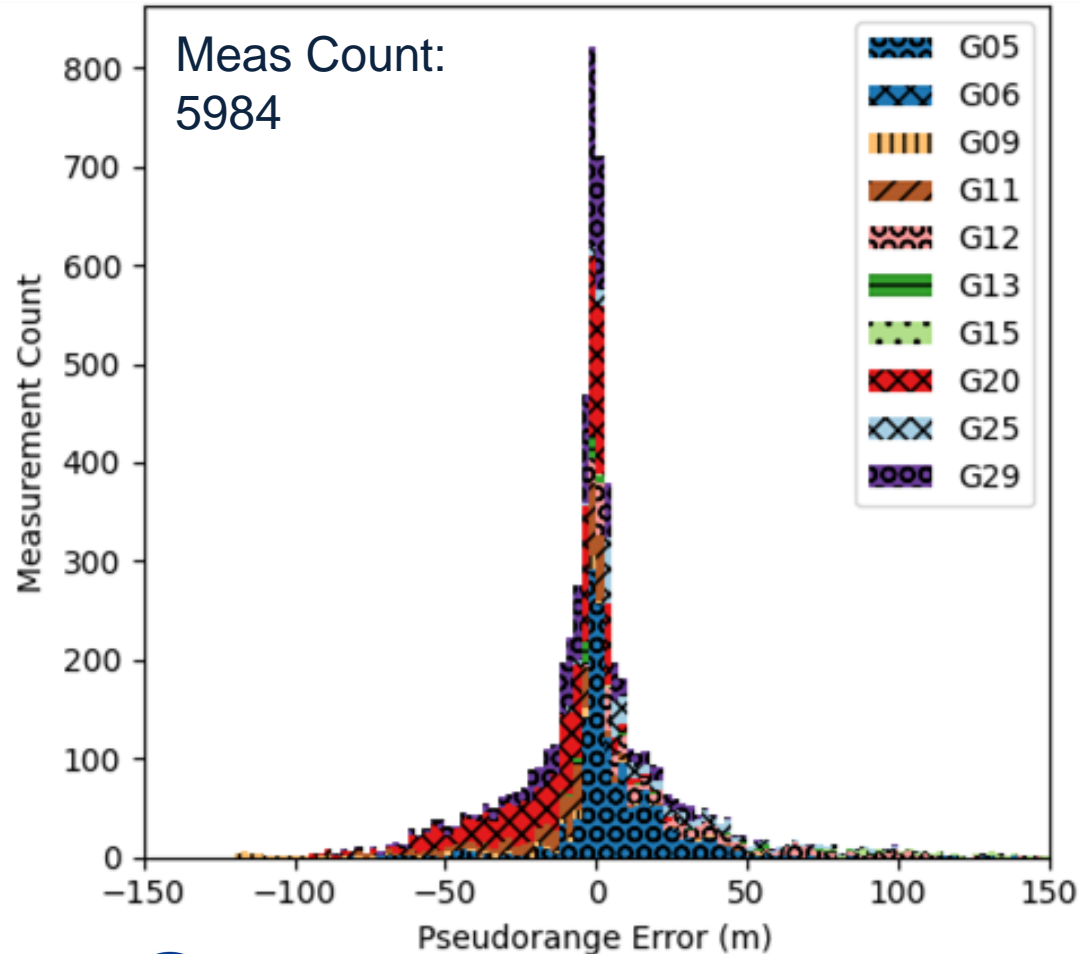
Boston, MA, USA



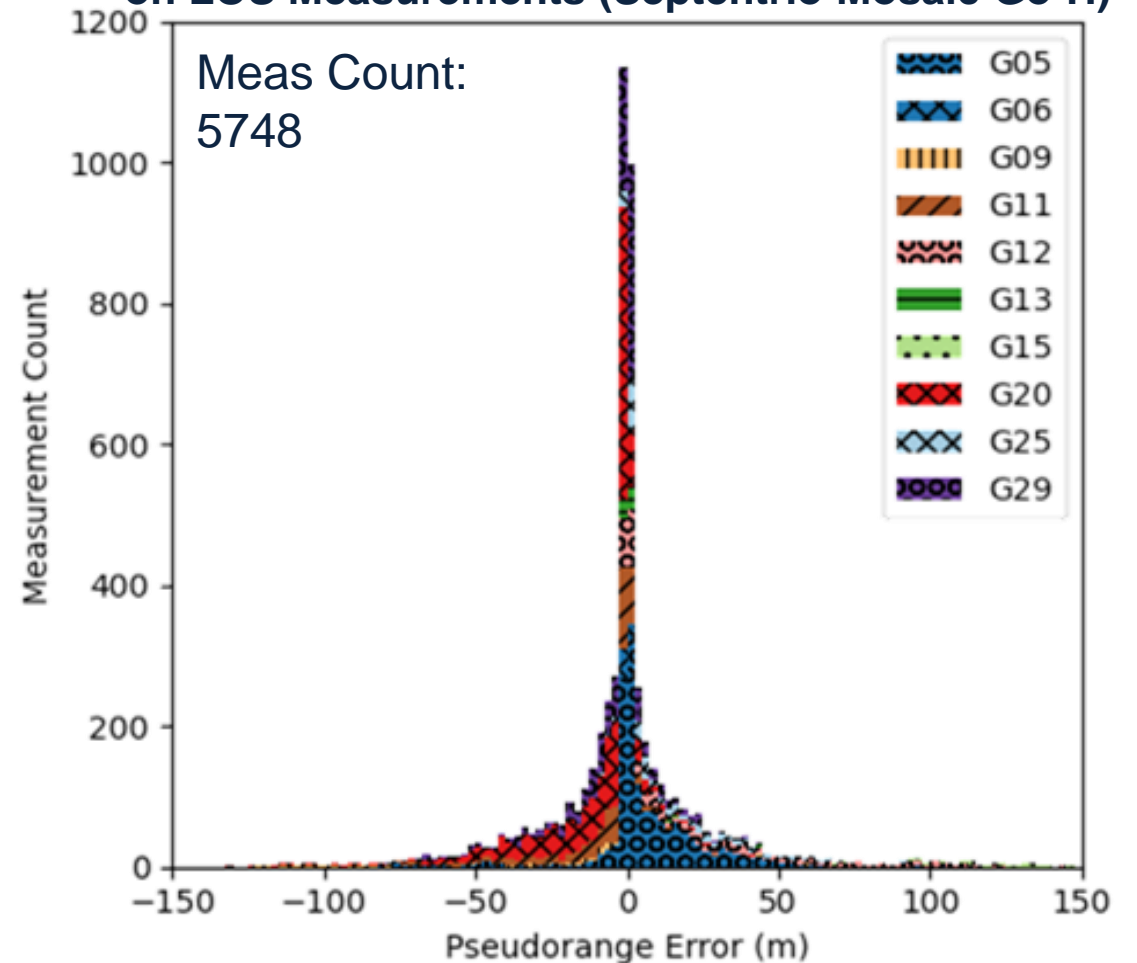
Results

The LOS measurements from both test receivers experience near-zero-mean, generally symmetric pseudorange error distributions

Statistical Behavior of Multipath Error on LOS Measurements (u-Blox M8)



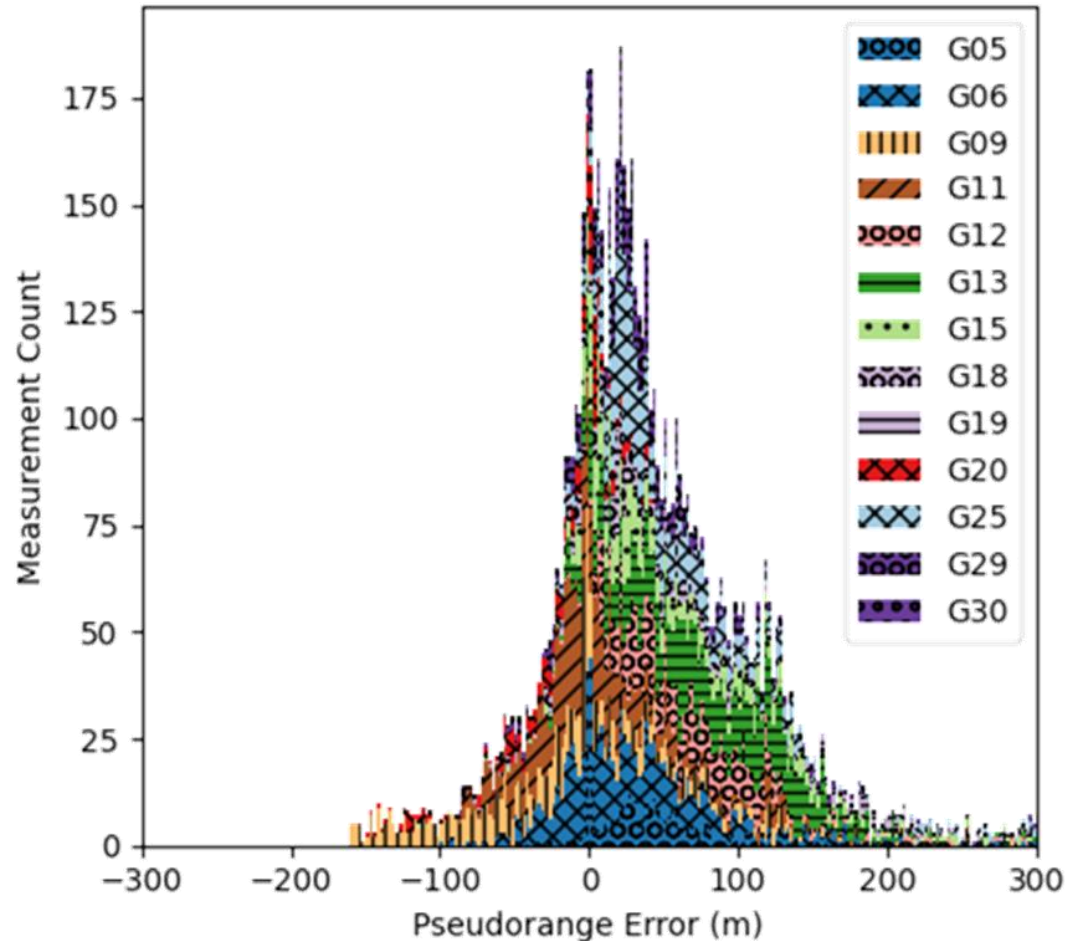
Statistical Behavior of Multipath Error on LOS Measurements (Septentrio Mosaic Go-H)



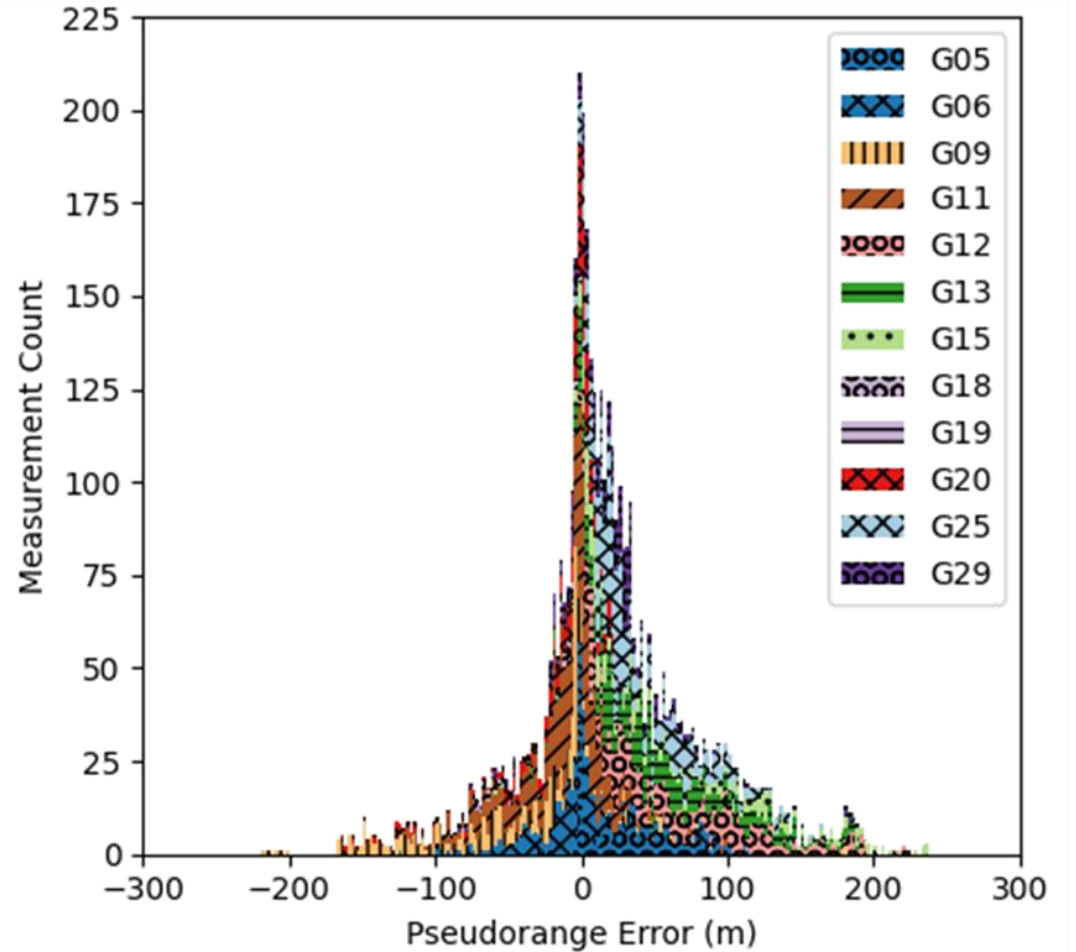
Results

The NLOS measurements from both test receivers experience non-zero-mean, right-tailed pseudorange error distributions

Statistical Behavior of NLOS Reception Errors on NLOS Measurements (u-Blox M8)



Statistical Behavior of NLOS Reception Errors on NLOS Measurements (Septentrio Mosaic Go-H)

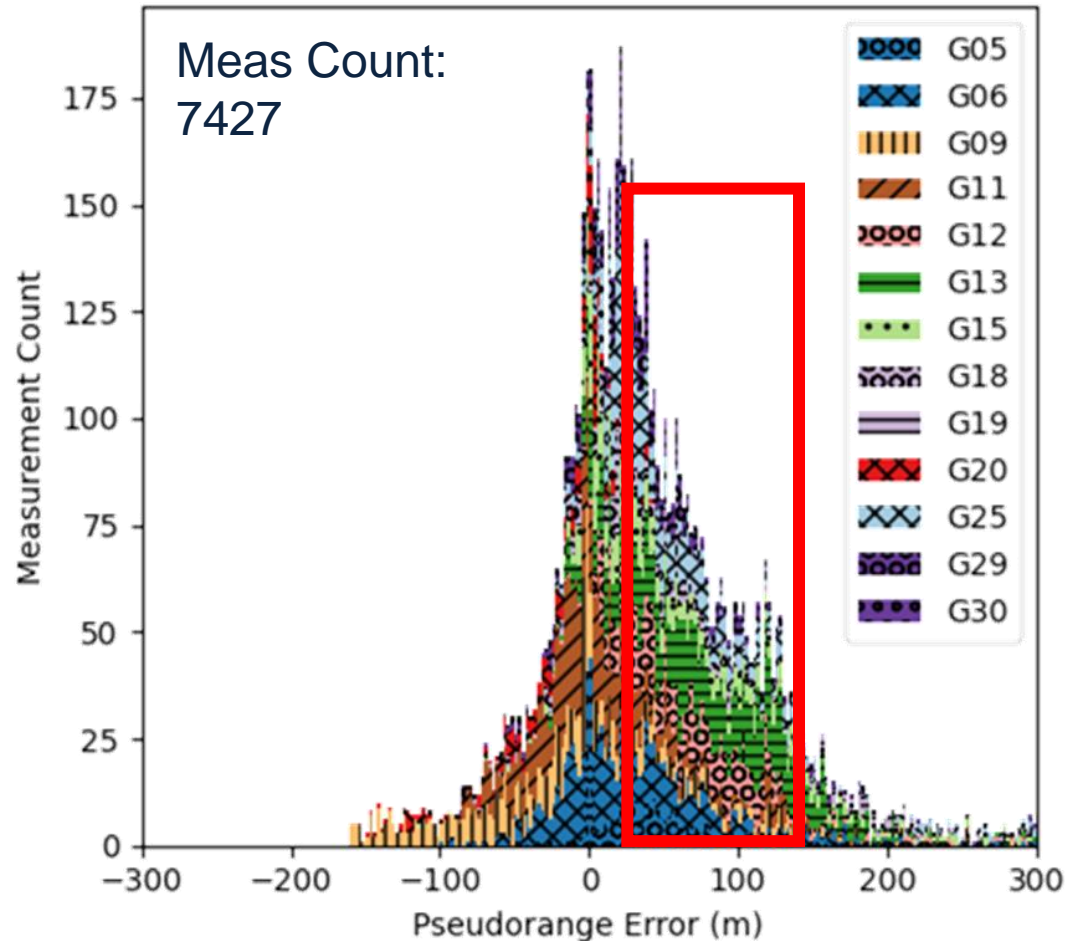


LOS: Line of Sight
NLOS: Non-Line of Sight

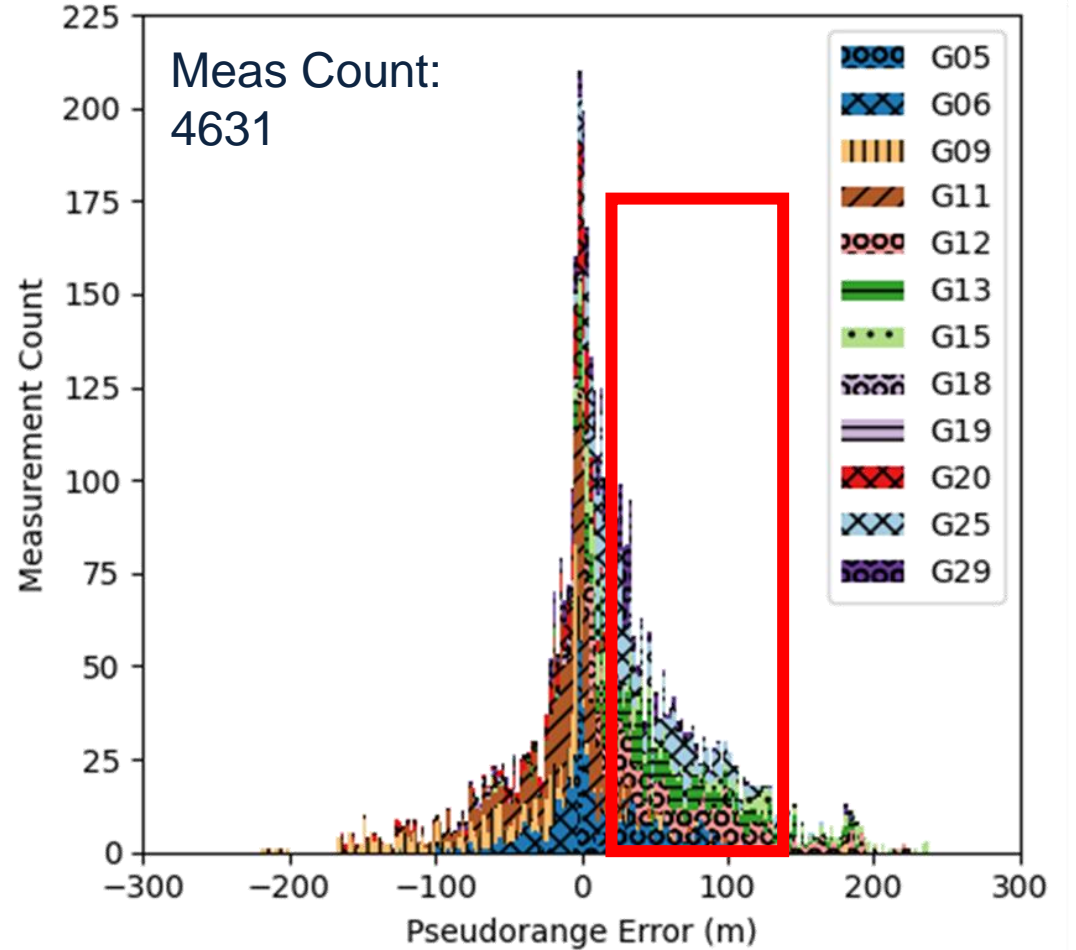
Results

The Septentrio receiver produced fewer measurements than the u-Blox receiver over the same trajectory

Statistical Behavior of NLOS Reception Errors on NLOS Measurements (u-Blox M8)



Statistical Behavior of NLOS Reception Errors on NLOS Measurements (Septentrio Mosaic Go-H)



Results

Primary takeaway: commonalities and differences observed in pseudorange error distribution shape, size, and scale across receivers

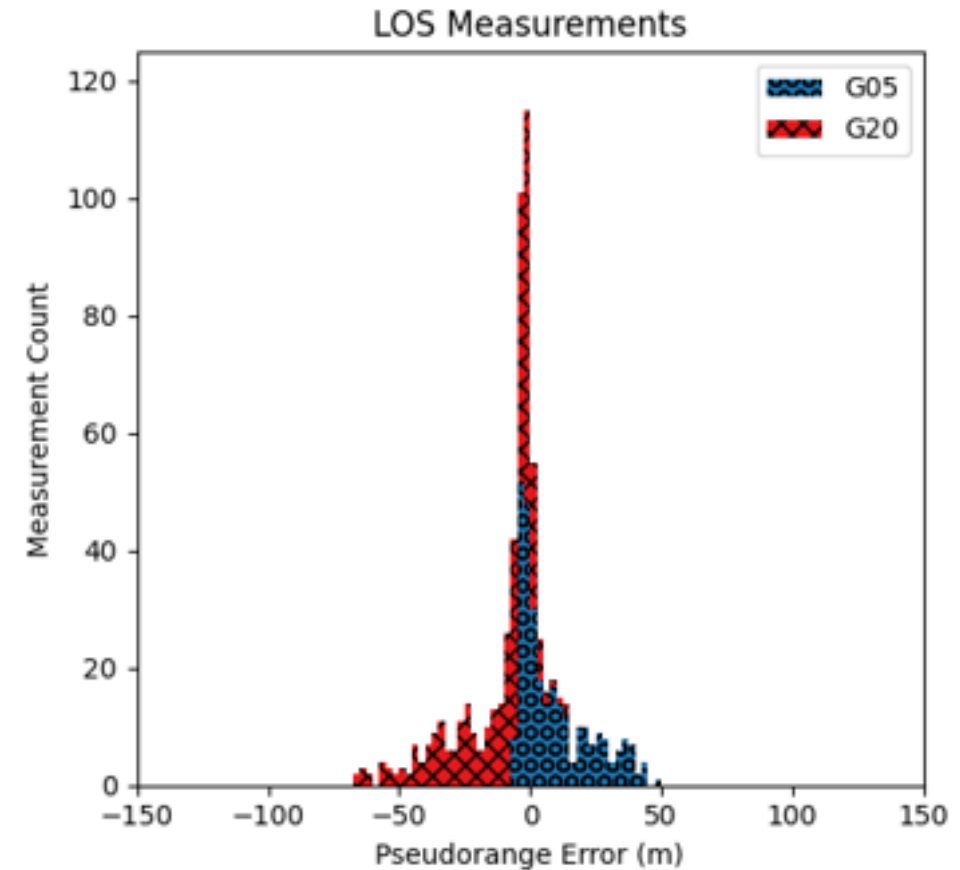
Metric	u-Blox M8	Septentrio Mosaic
LOS Meas. Count	5984 meas	5748 meas
LOS Meas. Mean and Median	0.5 m (mean), -0.6 m (median)	0.3 m (mean), -0.2 m (median)
LOS Meas. Errors [25m, 125m)	11.4%	10.1%
NLOS Meas. Count	7427 meas	4631 meas
NLOS Meas. Mean and Median	53.2 m (mean), 31.0 m (median)	22.7 m (mean), 12.9 m (median)
NLOS Meas. Errors [25m, 125m)	41.6%	32.6%

Accuracy and availability requirements are necessary for navigation risk mitigation [1]

- This table does not imply one receiver is “better”
- Employ navigation strategies to best leverage performance characteristics (path planning, data fusion)
- Other mission requirements include form factor, power, computation cost...

Conclusions

- Trends: NLOS reception ranging errors have non-zero-mean and tailed distributions
 - This work and the prior work ([3]) are exemplars of pseudorange error distribution as a function of select urban canyon properties
 - Canyon classification metrics computed from digital elevation maps enable comparison across datasets
- Future work
 - Study how navigation-domain errors behave in the presence of these pseudorange-domain errors (least squares solvers, Kalman filters, integrity metrics)
 - Further pseudorange error characterization (variation over tracking loops, receiver velocity, time)

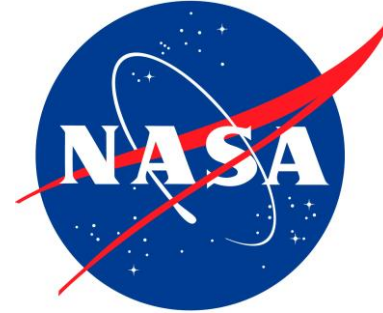


More results in paper,
including discussion of distribution
of errors from individual satellites

References

- [1] United States Department of Defense, United States Department of Homeland Security, & United States Department of Transportation. (2022, July 1). 2021 Federal Radionavigation Plan (Report No. DOT-VNTSC-OST-R-15-01). United States Department of Transportation, Office of Positioning, Navigation and Timing (PNT) & Spectrum Management; United States Department of Transportation, Office of the Assistant Secretary for Research and Technology. Retrieved from /view/dot/63024
- [2] DeCleene, B. (2000, September). Defining pseudorange integrity - Overbounding. In Proceedings of the 13th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GPS 2000) (pp. 1916–1924). Salt Lake City, UT.
- [3] Peretic, M., Gilabert, R., Carroll, J., Gutierrez, J., Moore, A., Christie, J., and Dill, E. (2025). Statistical analysis of GNSS multipath errors in urban canyons. In 2025 IEEE/ION Position, Location and Navigation Symposium (PLANS), pages 1216–1225, Salt Lake City, Utah.
- [4] Matera, E. R., Garcia-Pena, A., Julien, O., Milner, C., and Ekambi, B. (2019). Characterization of line-of-sight and non-line-of-sight pseudorange multipath errors in urban environment for GPS and Galileo. In Proceedings of the 2019 International Technical Meeting of The Institute of Navigation, pages 177–196, Reston, Virginia.
- [5] Chen, X. (2018). Statistical multipath model comparative analysis of different GNSS orbits in static urban canyon environment. *Advances in Space Research*, 62(5):1034–1048.
- [6] Wang, Y., Chen, X., and Liu, P. (2018). Statistical multipath model based on experimental GNSS data in static urban canyon environment. *Sensors*, 18(4).
- [7] Gutierrez, J., Young, S., Moore, A., Gilabert, R., Dill, E., Bates, E., Peretic, M., Schmitt, K., and Scholz, A. (2024). A High-Performance Computing Predictive GNSS Performance Monitor for Autonomous Air Vehicles in Urban Environments. Technical Report 20240009932, NASA Langley Research Center, Hampton, VA.
- [8] Dill, E., Gutierrez, J., Young, S., Moore, A., Scholz, A., Bates, E., Schmitt, K., and Doughty, J. (2021). A predictive GNSS performance monitor for autonomous air vehicles in urban environments. In Proceedings of the 34th International Technical Meeting of the Satellite Division of The Institute of Navigation (ION GNSS+ 2021), pages 125–137, St. Louis, Missouri.

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Questions?

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Special thanks to Dr. Sharon Marroquin¹, Ryan Cassel¹, Dr. Steve Langel¹, Dr. Michael Zowada¹, Dr. Esther Conrad, and Dr. Sarah Lehman² for their helpful discussions, review, and support on the graphics!

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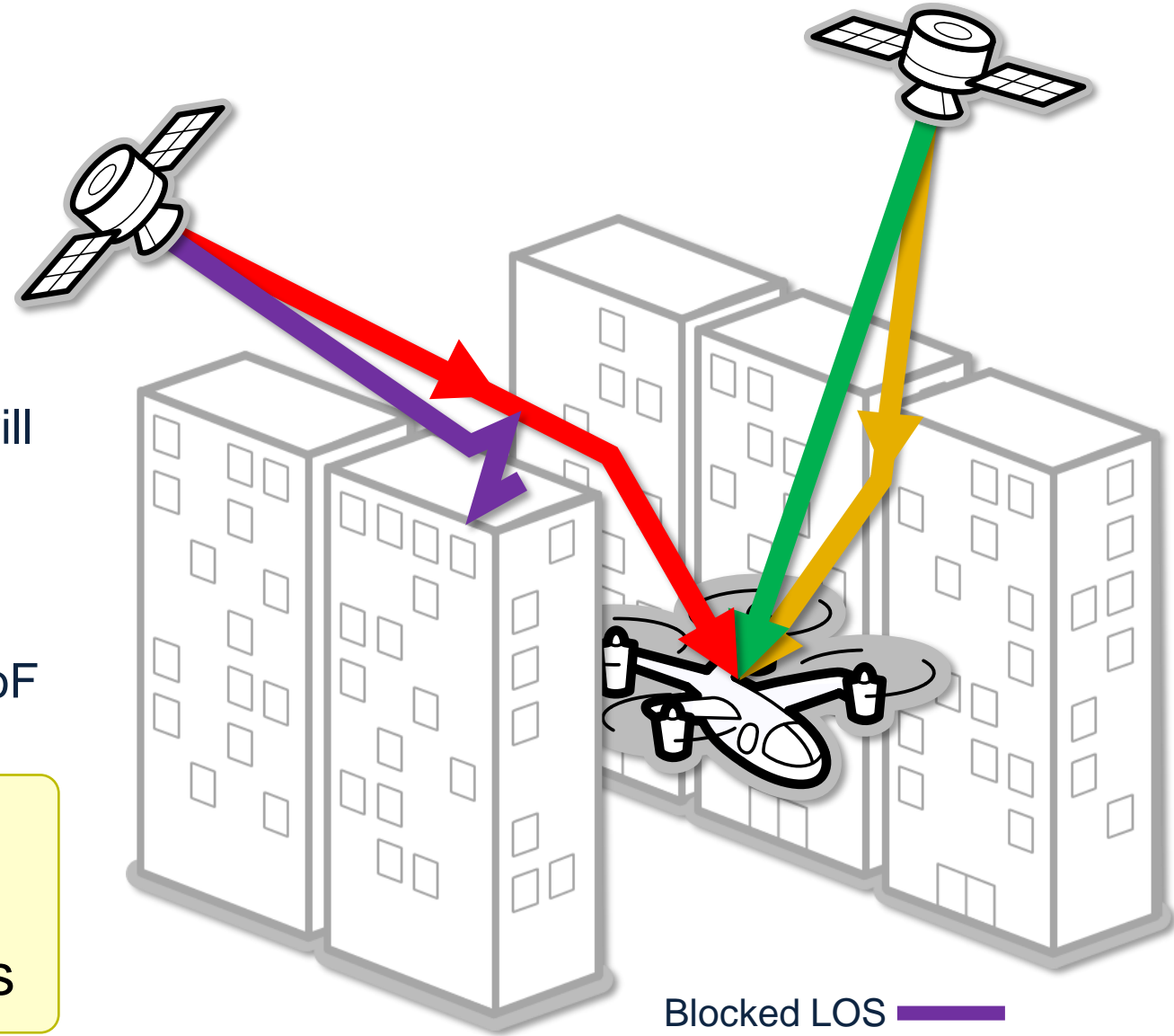
Backup

Introduction

Urban canyons can be challenging for GNSS-based navigation

- Buildings can block the LOS to satellites
- A GNSS signal reflection from a building will have a longer time of flight (ToF)
- Multiple reflections can interfere with each other (known as multipath), lengthening or shortening the measured ToF

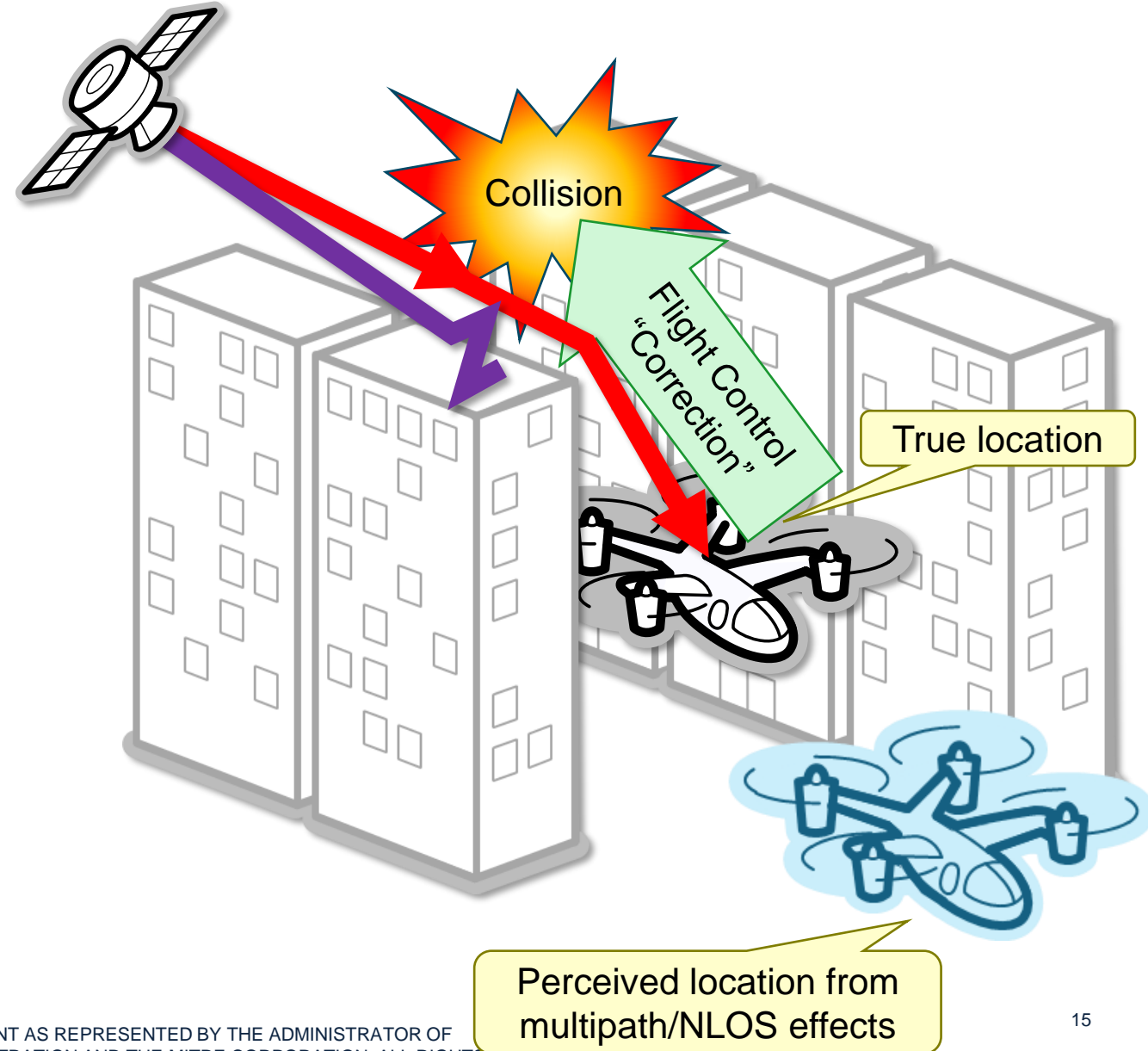
This work: statistical findings from empirical data of the impact of these effects on pseudorange measurements



- Blocked LOS █
- NLOS Reflection █
- LOS Signal █
- Multipath Reflection █

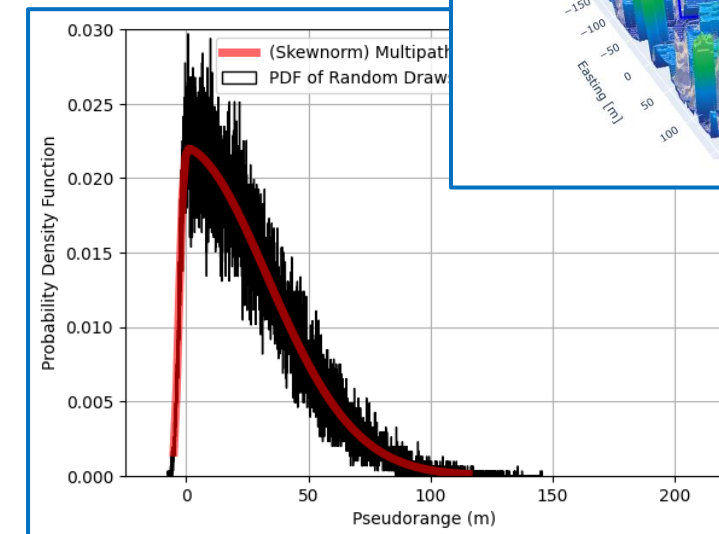
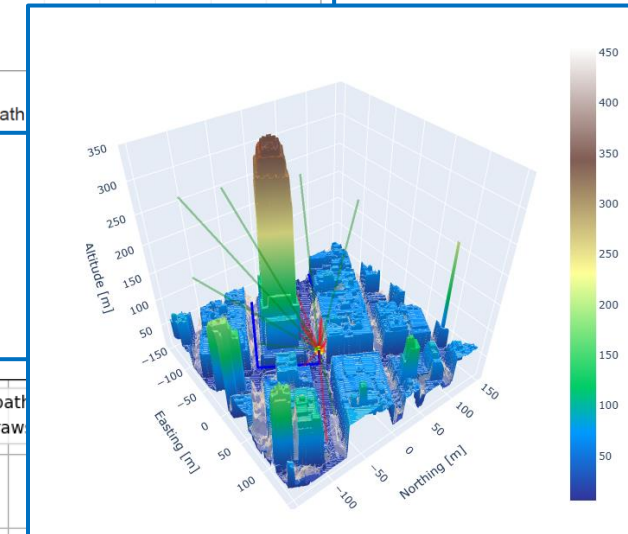
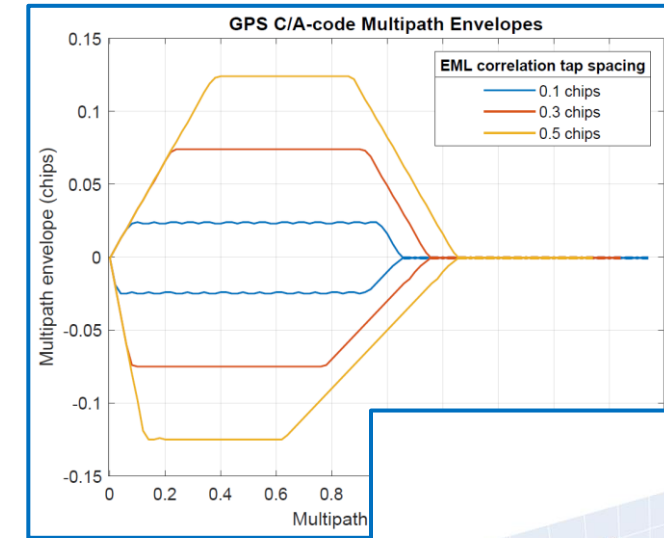
Motivation

- Navigation risk assessment
 - What capabilities does a GNSS receiver need to safely operation in a given urban environment?
 - When and where should alternative navigation techniques be employed?
- Better understanding these pseudorange errors can inform...
 - Navigation risk assessment techniques (integrity, modsim, and error bounding)
 - Urban-resilient receiver design (tracking loops, nav solvers, measurement rejection)



Motivation

- Navigation risk assessment
 - What capabilities does a receiver need for operation in a given urban environment?
 - What technical analysis is required to approve an urban mission employing GNSS-based navigation?
 - When and how should complementary navigation techniques be used?
- Better understanding of these pseudorange errors can inform...
 - Navigation risk assessment techniques (integrity, modsim, and error bounding)
 - Urban-resilient receiver design (tracking loops, nav solvers, measurement rejection)



Introduction

Background

Urban Air Mobility

- Emergency services
- Urban logistics
- New business models (air taxis, etc.)

Mission Risk Analysis

- One approach: pre-mission prognostic services
- Multi-modal risk assessment: sensors, control, health... need common technical currency

GNSS Rx Performance

Pseudorange error analysis

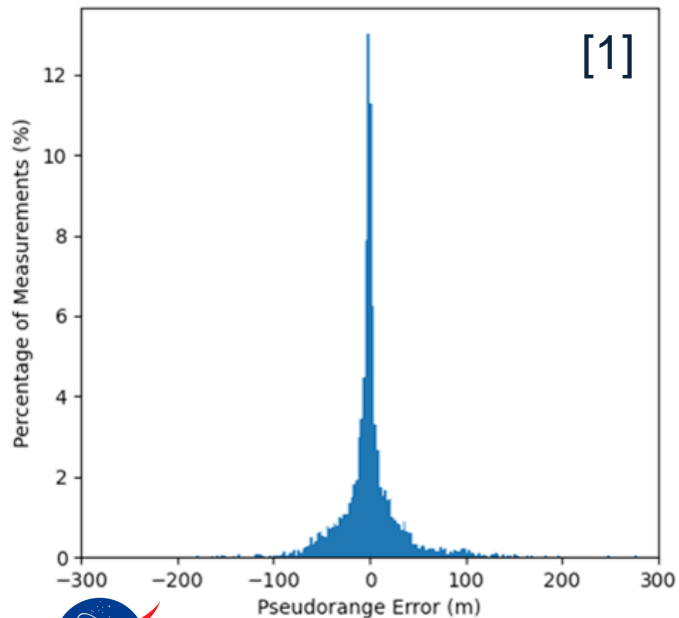


Nav solver error analysis



Nav filter error analysis

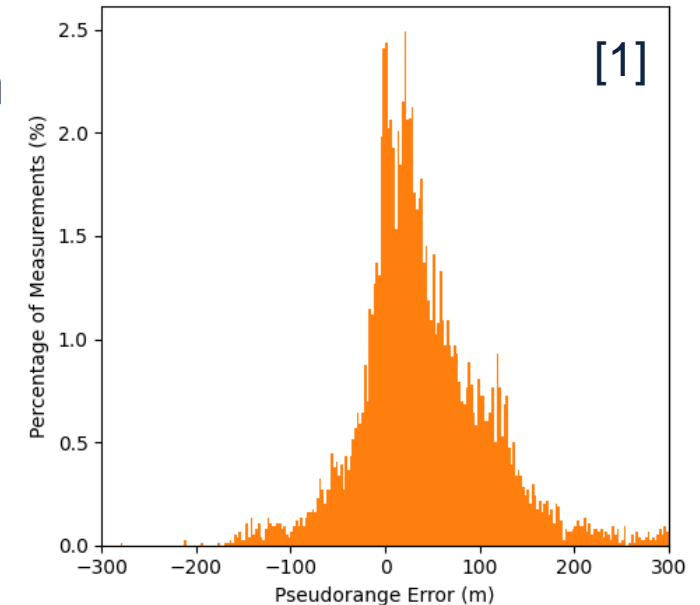
Underlying Questions



In the presence of multipath and NLOS reception, are pseudorange errors...

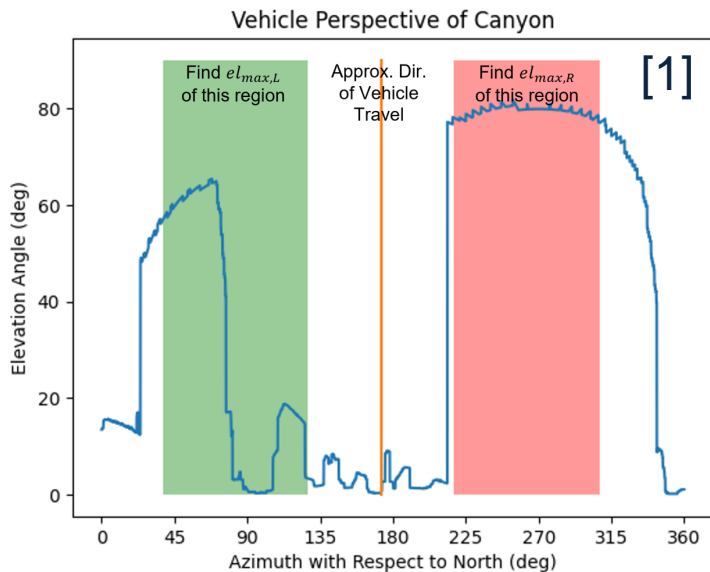
...zero-mean symmetric?

...or not?

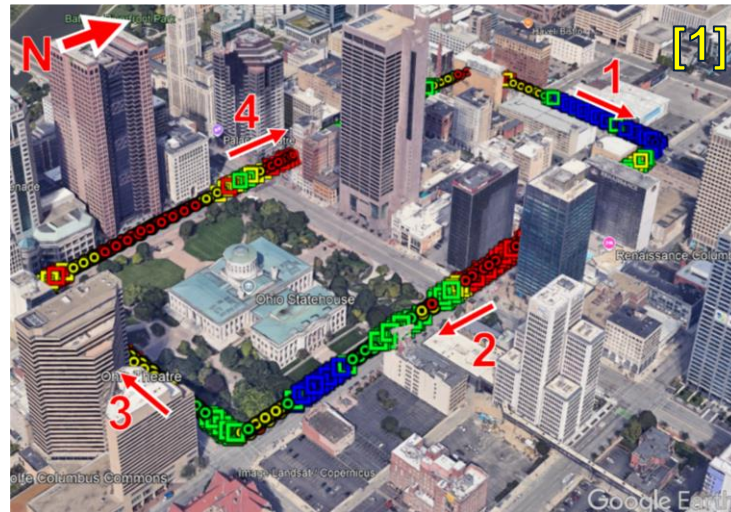


Background

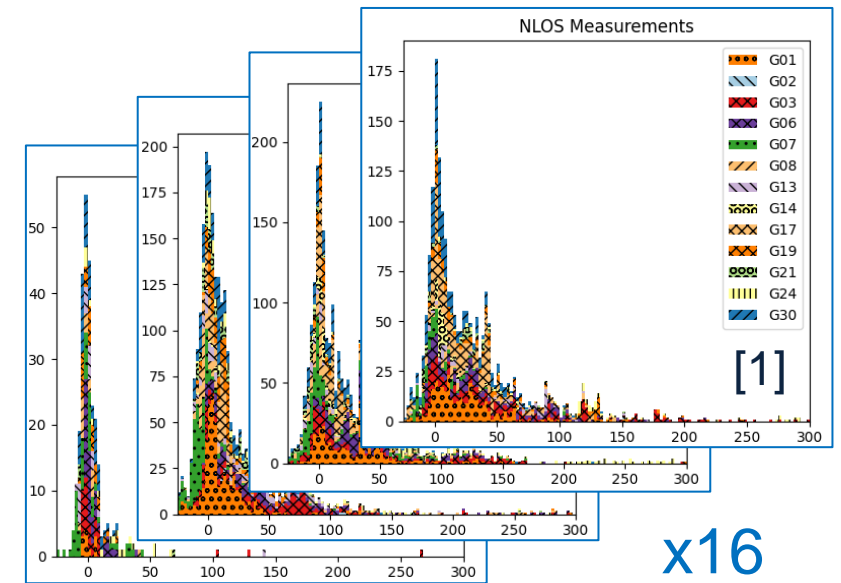
- Few publications have **empirically** studied statistical behavior of multipath and NLOS pseudorange errors [2, 3, 4]
- Our prior work: *Statistical Analysis of GNSS Multipath Errors in Urban Canyons* (ION PLANS 2025) [1]



Canyon depth and LOS/NLOS analysis using Digital Elevation Map



Classification of each point along the trajectory using canyon depth metrics



Multipath and NLOS reception errors exhibit positive error tails when the measurements are NLOS



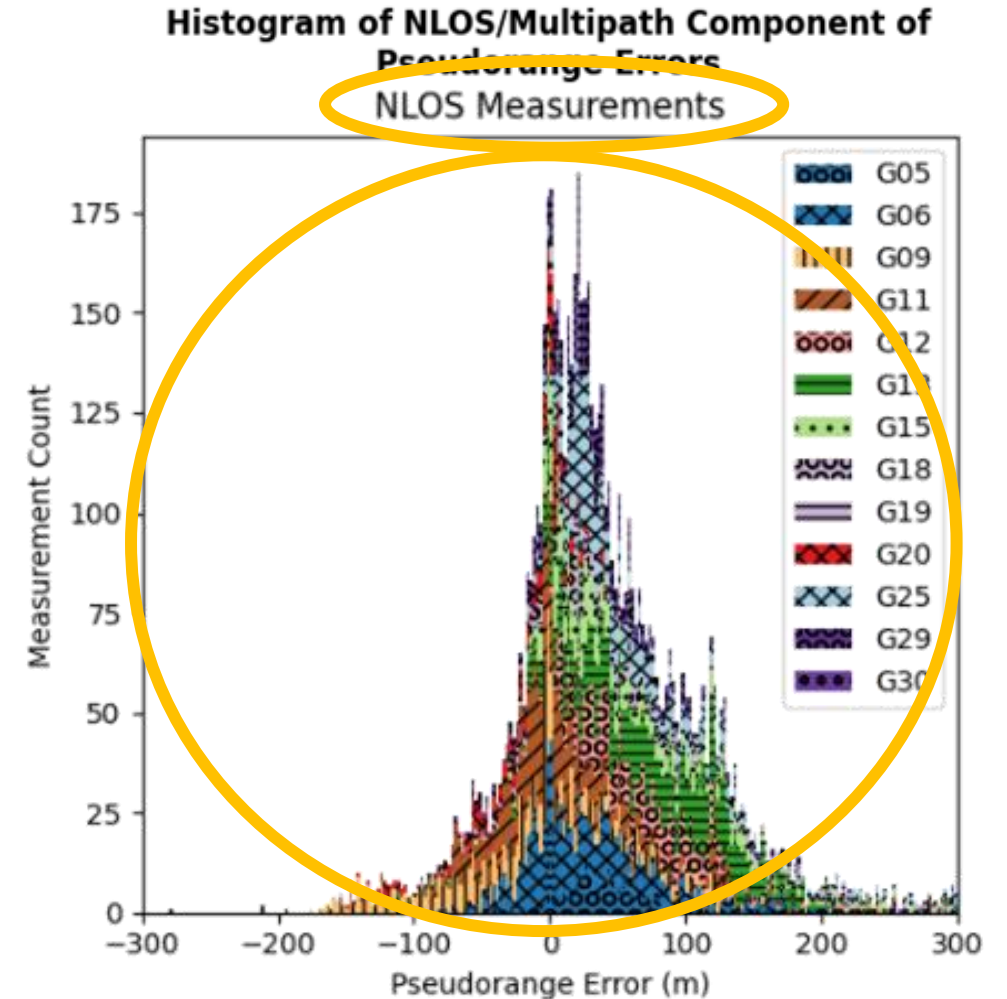
LOS: Line of Sight
NLOS: Non-Line of Sight

Agenda

This paper: do similar trends emerge...

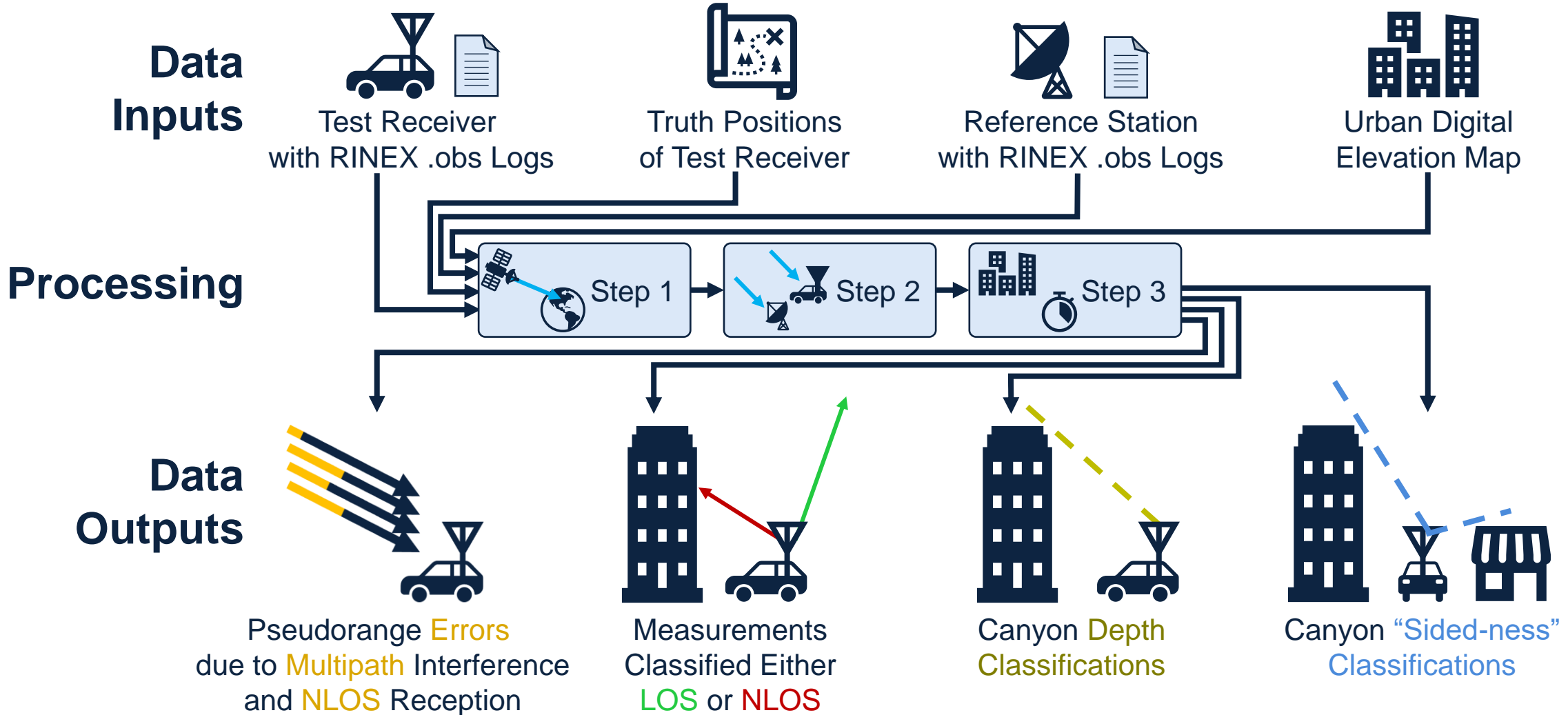
1. ...for different commercial receivers?
2. ...in a different city?

- This talk:
 - How to get “NLOS/Multipath Component of Pseudorange Error” from empirical measurements
 - Axes, legend, and data series in the plots
- Overview of results in the paper
 - Trends in statistical behavior pseudorange error from LOS vs NLOS measurements
 - Quantitative comparison between receivers



Multipath Error Isolation

See paper for details on the three processing steps

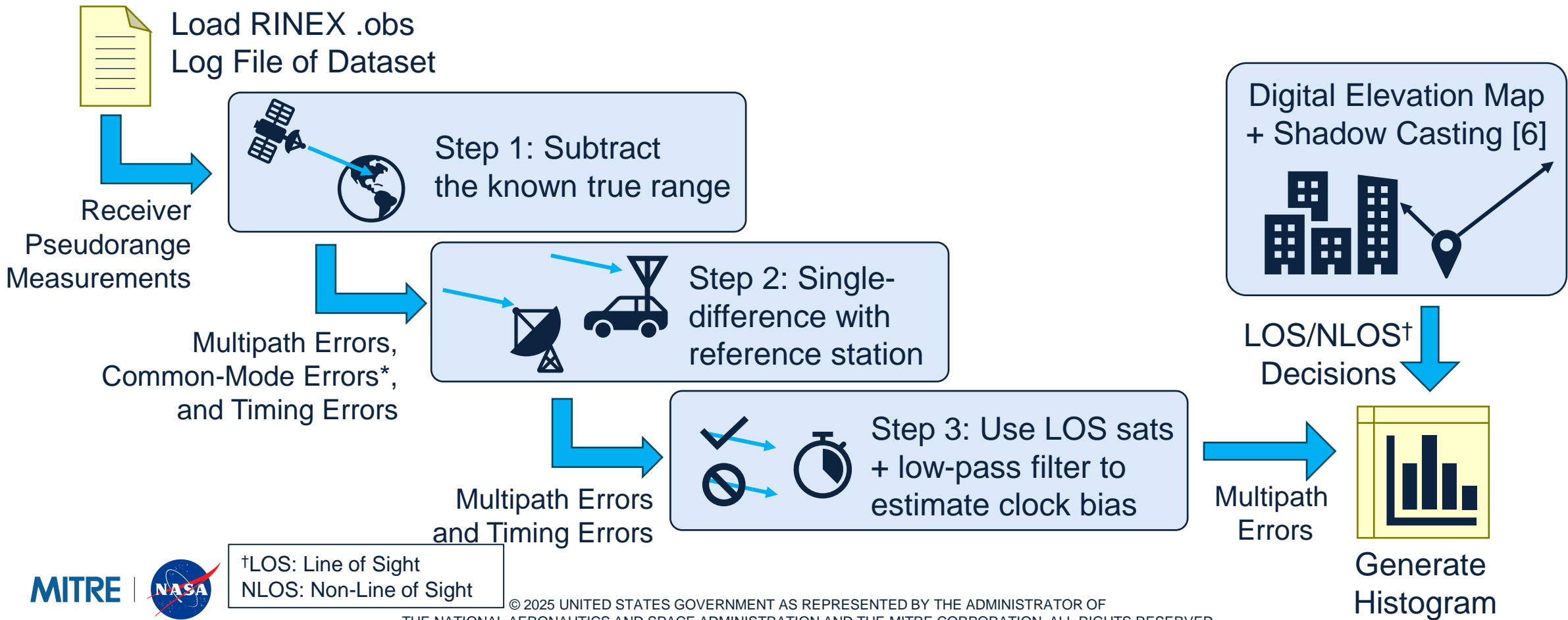


LOS: Line of Sight
NLOS: Non-Line of Sight

Multipath Error Isolation

* For example, atmospheric, relativistic, satellite position, and satellite clock errors.
See [4] and [5] for more on these Common-Mode Errors and the single-differencing technique.

Subtract other modellable/cancellable error sources to study the multipath error in pseudorange measurements from a commercial receiver.



[†]LOS: Line of Sight
NLOS: Non-Line of Sight



Dataset Overview

Boston, MA, USA



	Columbus, OH (Prior Work [4])	Boston, MA (This Work)
Test Receiver Models	1 receiver: u-Blox F9R	2 receivers: u-Blox M8, Septentrio Mosaic Go-H
Truth Receiver Capability	<ul style="list-style-type: none"> L1+L2 multi-GNSS Altitude clamping Inertial aiding 	<ul style="list-style-type: none"> L1+L5 multi-GNSS Altitude clamping
Urban Landscape	Mix of canyon depths Mix of canyon "sidedness"	Higher concentration of deep, one-sided canyons
Trajectory	8 laps, ~3.5min per lap	6 legs, ~4.25min per leg

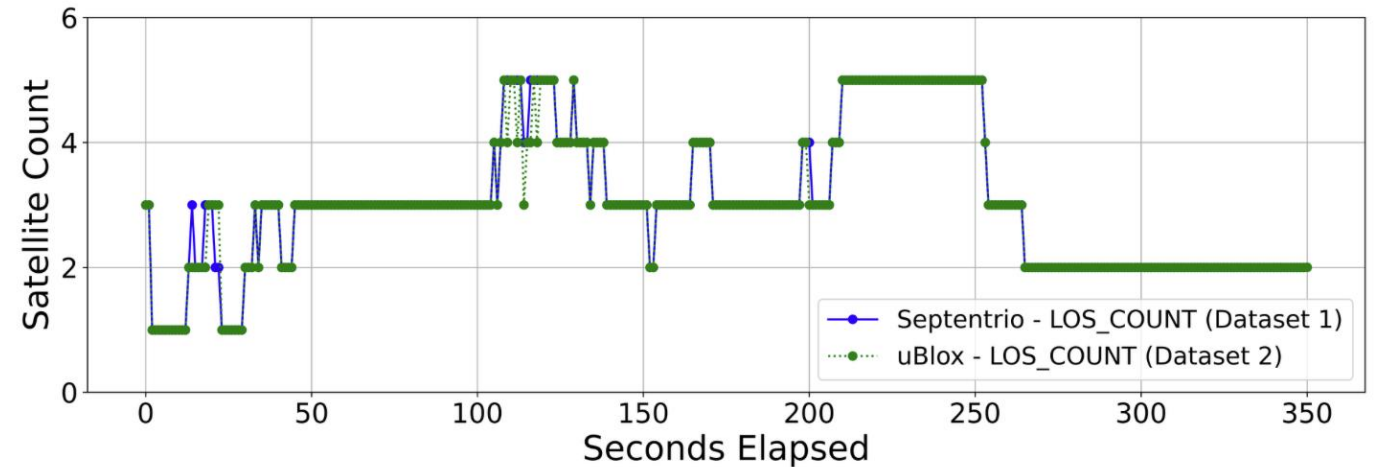
Max Elevation Angle to Top of Building on Deeper Side of Canyon	Map Icon Color
0 to 30°	Blue
30° to 55°	Green
55° to 70°	Yellow
70° to 90°	Red

- Square Icons: Two-sided Canyon (Difference in max elevation < 15°)
- Circle Icons: One-sided Canyon (Difference in max elevation ≥ 15°)

Dataset Overview

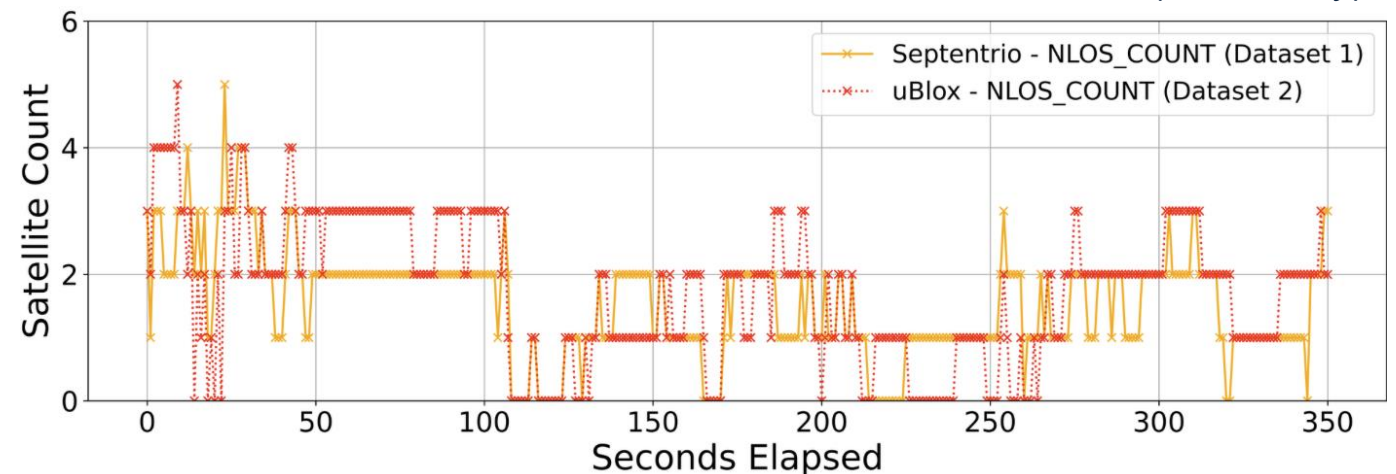
- LOS Measurements
 - Similar total number of measurements (4% difference)
 - Usually tracking same quantity of satellites

Time-Series of Test Receiver LOS Measurement Count (GPS Only)



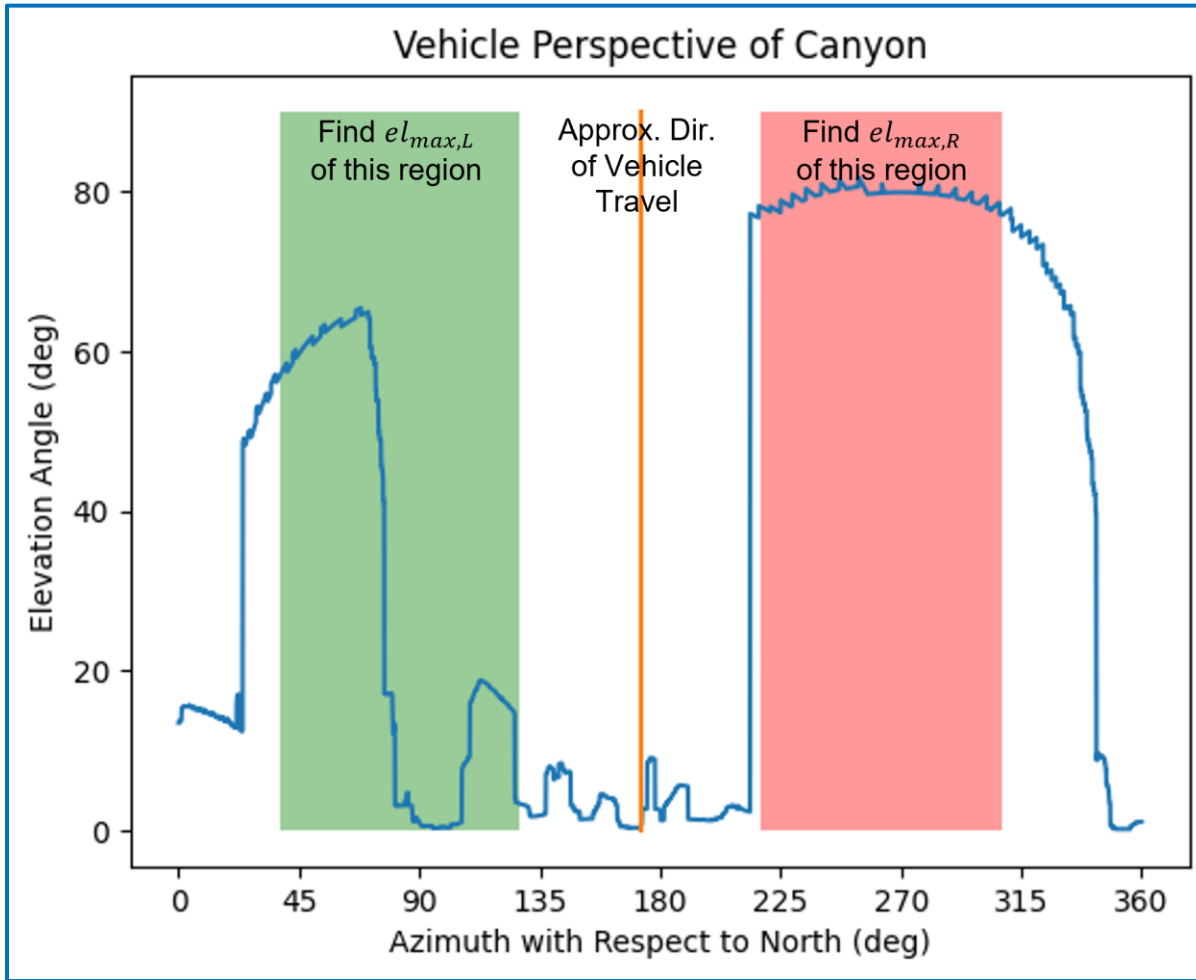
- NLOS Measurements
 - Nearly 2x measurements from the u-Blox compared to the Septentrio
 - Neither receiver consistently recording more measurements than the other

Time-Series of Test Receiver NLOS Measurement Count (GPS Only)



LOS: Line of Sight
NLOS: Non-Line of Sight

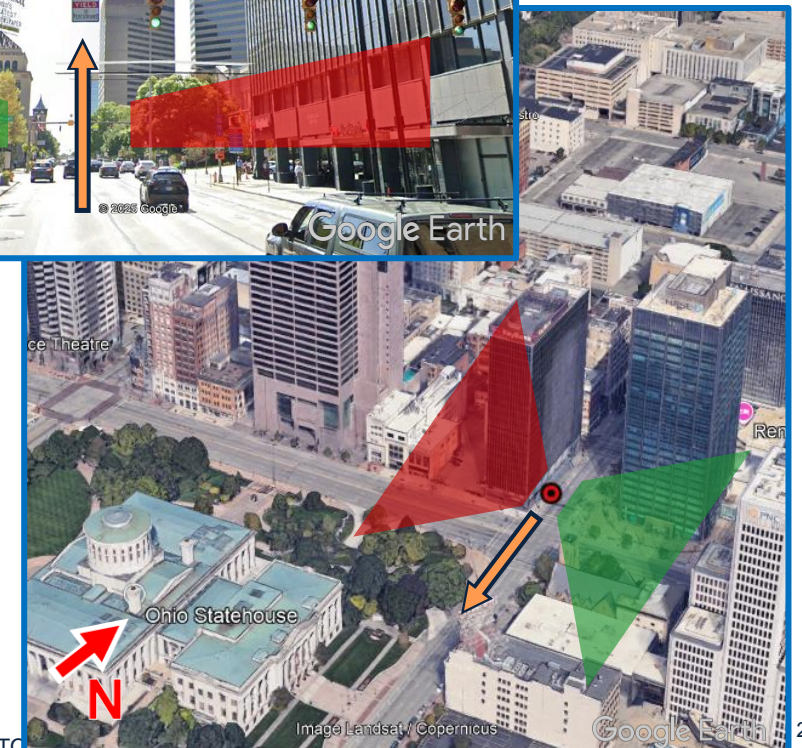
Prior Work ([3]): Canyon Depth Classification



Canyon contour generated from digital elevation map data



Orange arrow:
direction of
vehicle travel



Prior Work ([3]): Canyon Depth Classification

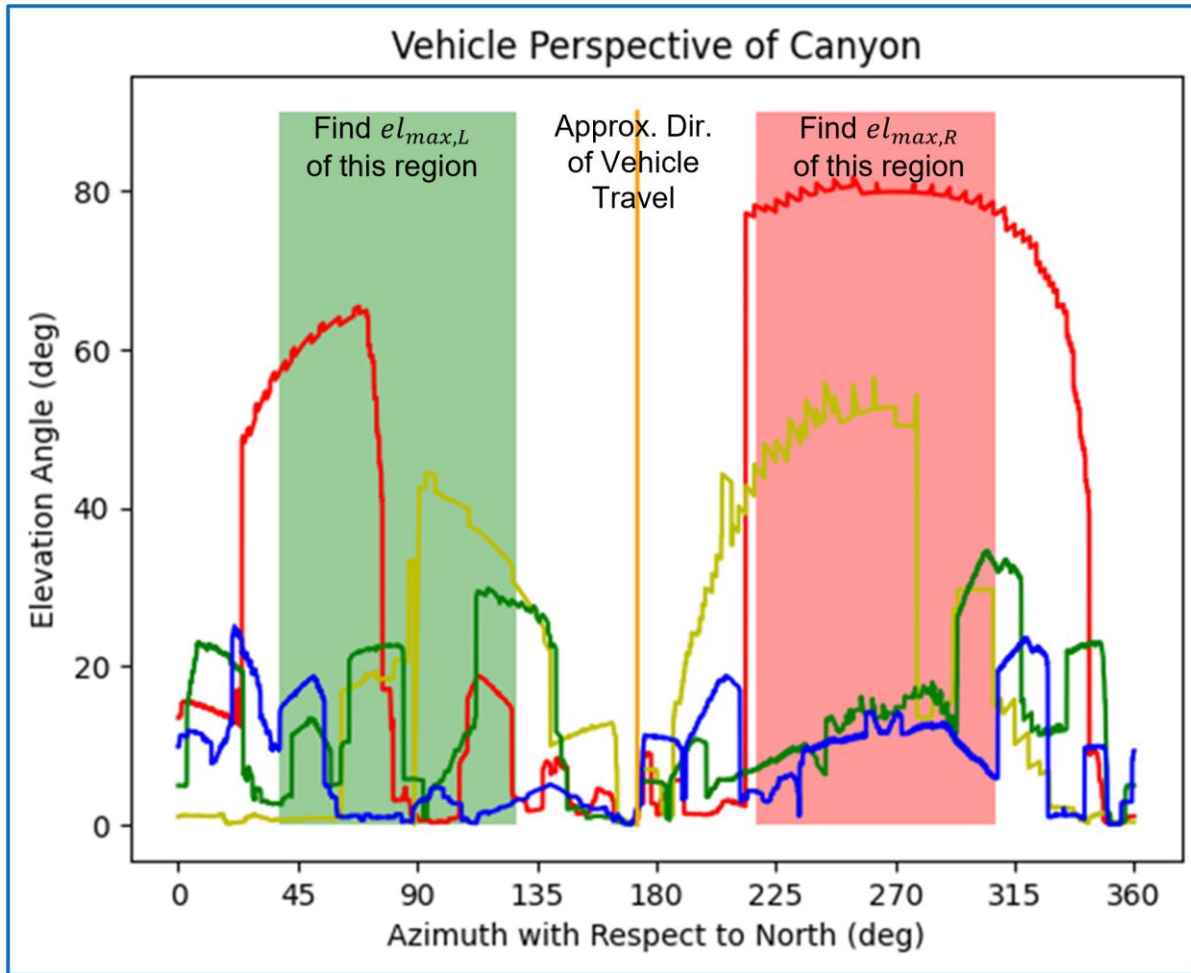


TABLE I: Urban Canyon Classification

Urban Canyon Depth Characterization Label	Max Elevation Angle to Top of Building on Deeper Side of Canyon	Map Icon Color
Open	0 to 30°	Blue
Shallow	30° to 55°	Green
Moderate	55° to 70°	Yellow
Deep	70° to 90°	Red

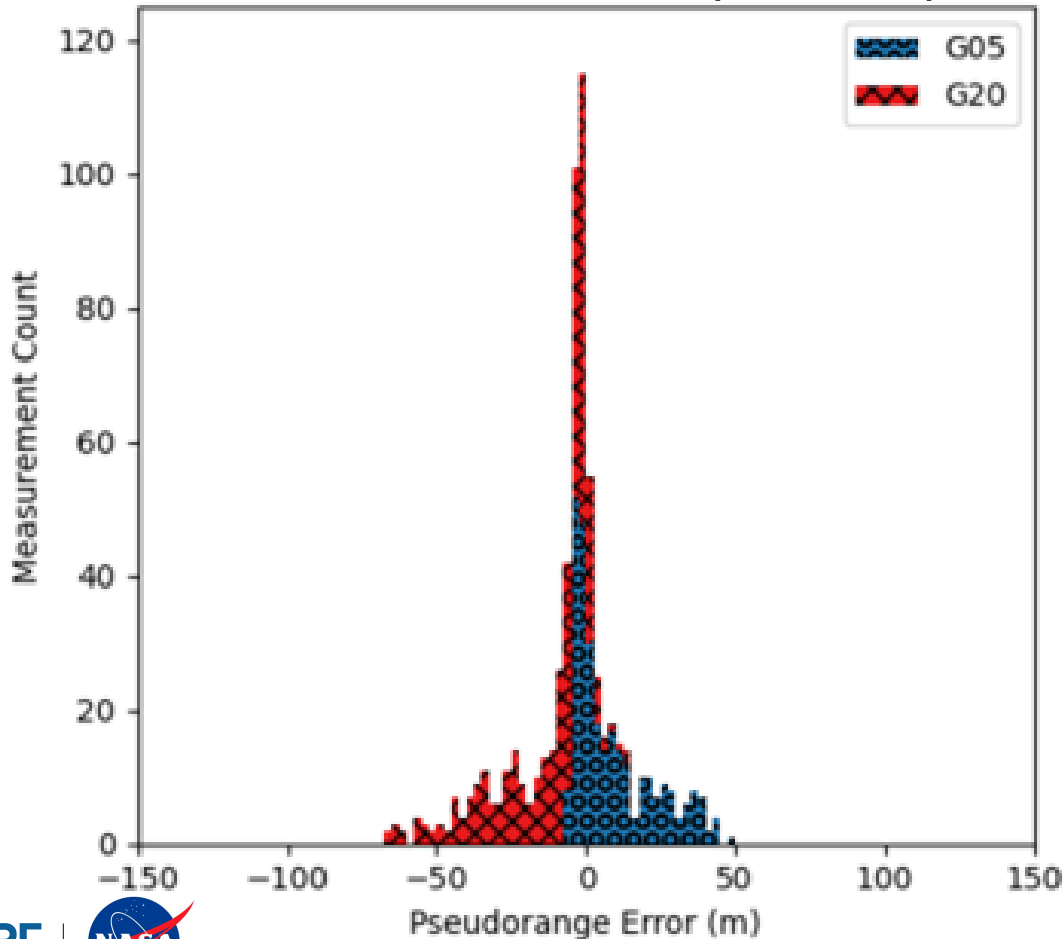
“One-sided” vs “two-sided” labels are determined by $|el_{max,L} - el_{max,R}|$:

- If greater than 15°, label “one-sided”
- If less than or equal to 15°, label “two-sided”

Per-Satellite Trends

LOS error distributions can differ by satellite in a manner consistent across commercial receivers.

Statistical Behavior of Multipath Error on LOS Measurements (u-Blox M8)



Statistical Behavior of Multipath Error on LOS Measurements (Septentrio Mosaic Go-H)

