

# Statistical Analysis of GNSS Multipath Errors in Urban Canyons

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# 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

Nav filter error analysis



Nav solver error analysis

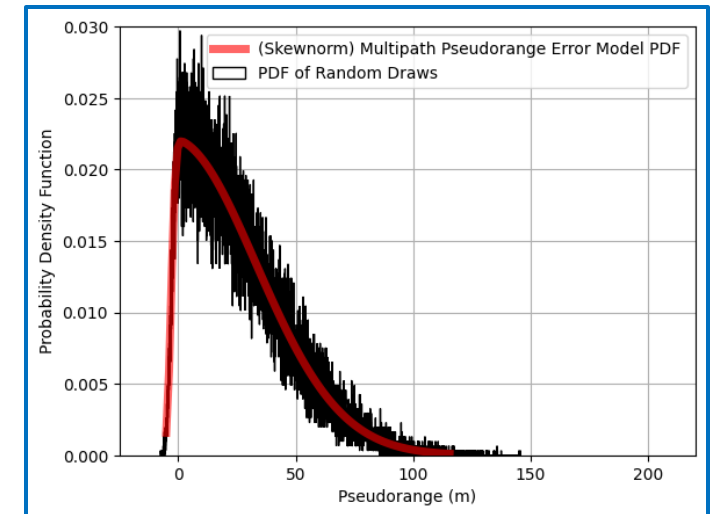


Pseudorange error analysis

Pseudorange measurement errors are often modeled as **Gaussian**... [1]

...but, **does that hold** for multipath interference and non-line of sight (NLOS) reception? [2]

...if not, what **generalizable conclusions** can be drawn to inform mission risk assessment?



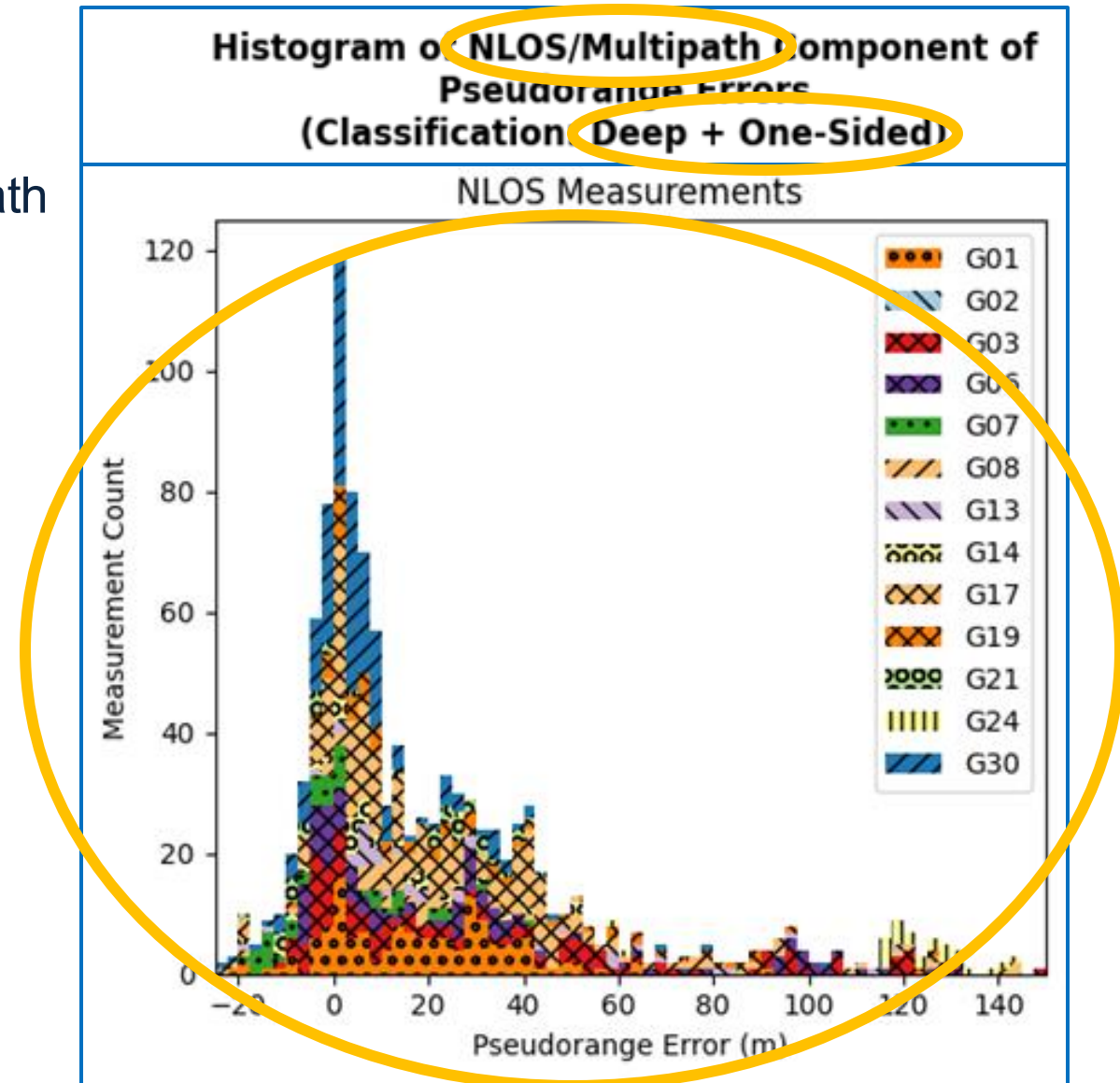
Recreation of results from [2]

## Research Questions



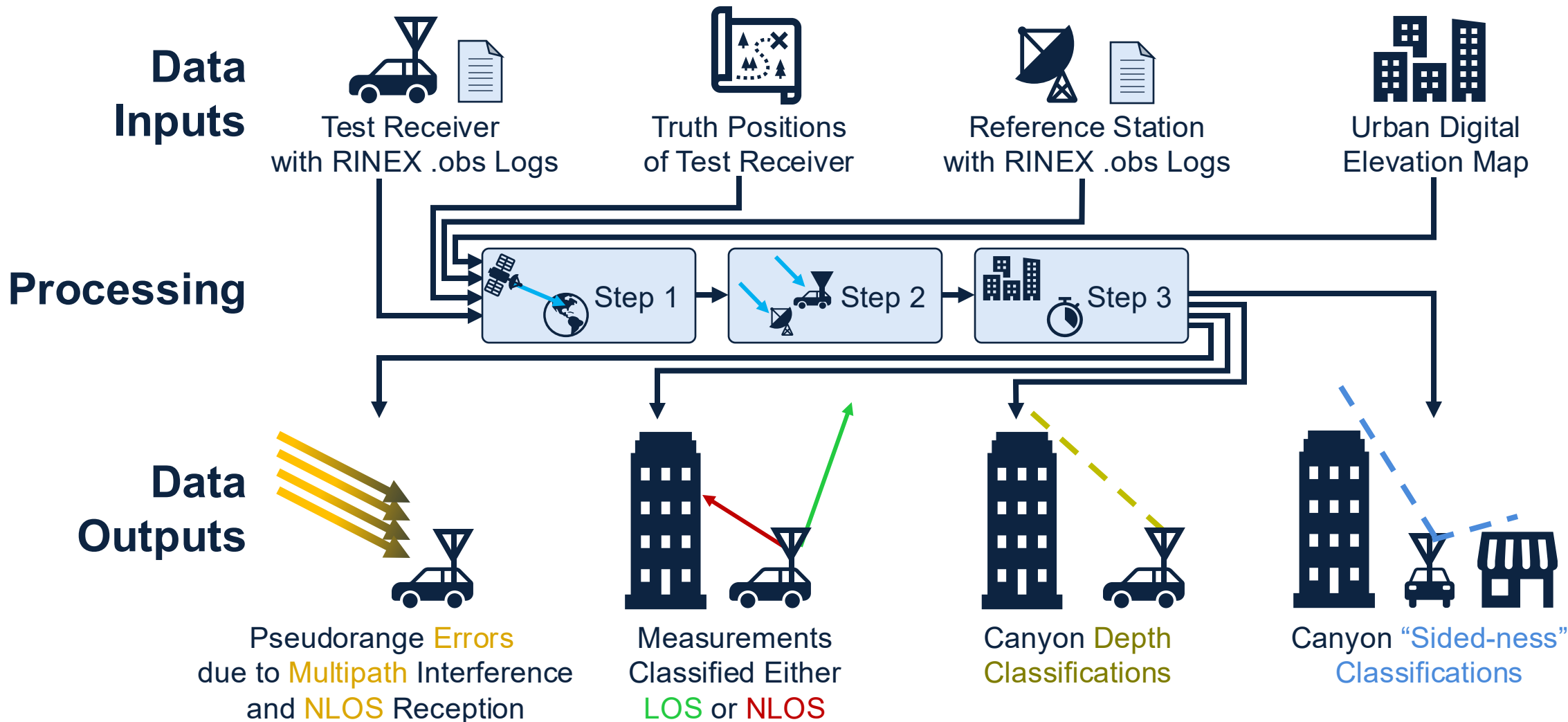
# Agenda

- How to read the plots
  - How to get “Pseudorange Error from Multipath Interference and NLOS Reception”?
  - What does “Deep + Two-Sided” mean?
  - Dataset description
- Overview of results in the paper
  - Line-of-Sight (LOS) measurements vs Non-Line-of-Sight (NLOS) measurements
  - Trends as canyon depth increases
  - Trends in “one-” vs “two-sided” canyons

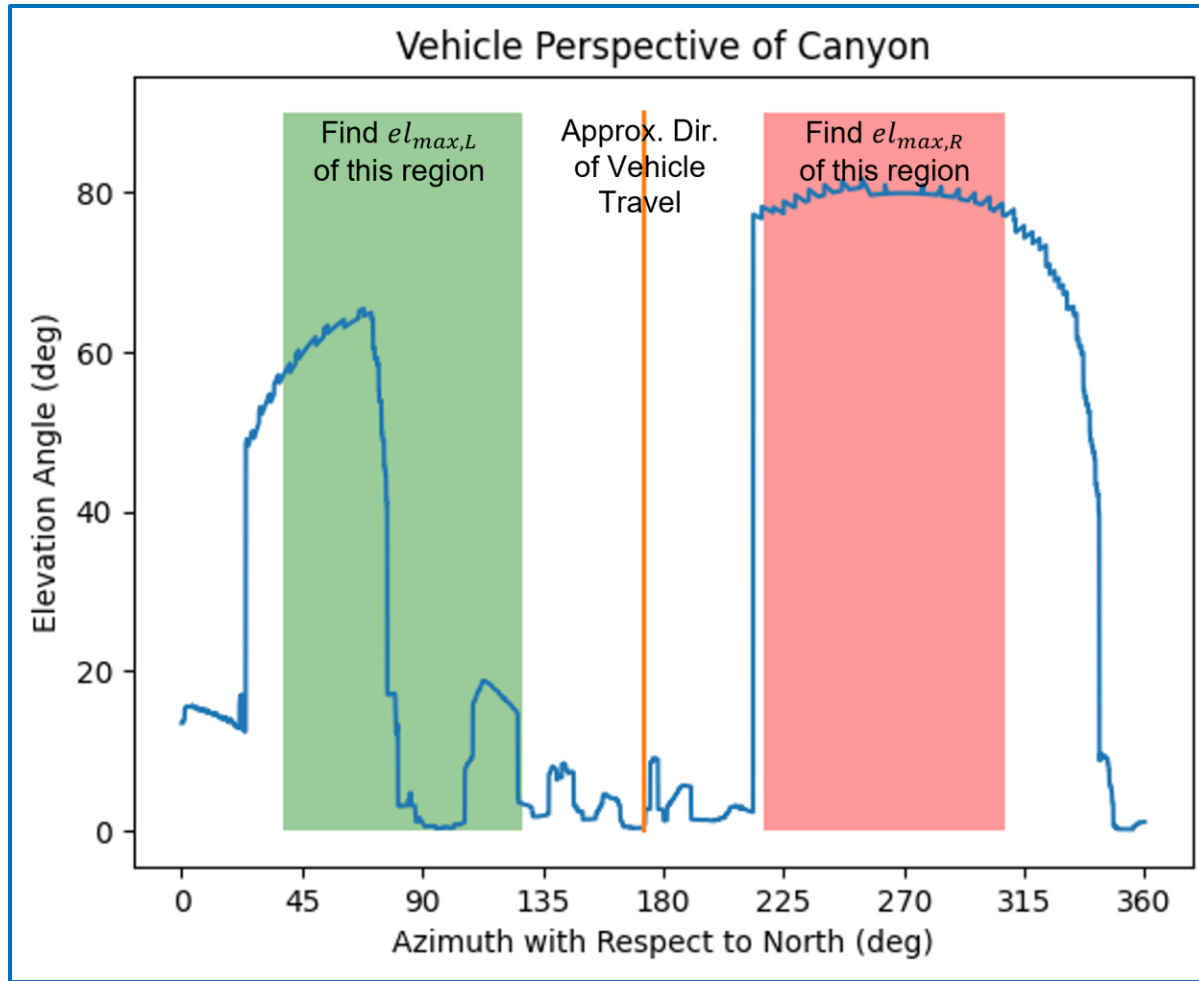


# Multipath Error Isolation

See paper for details on the three processing steps.



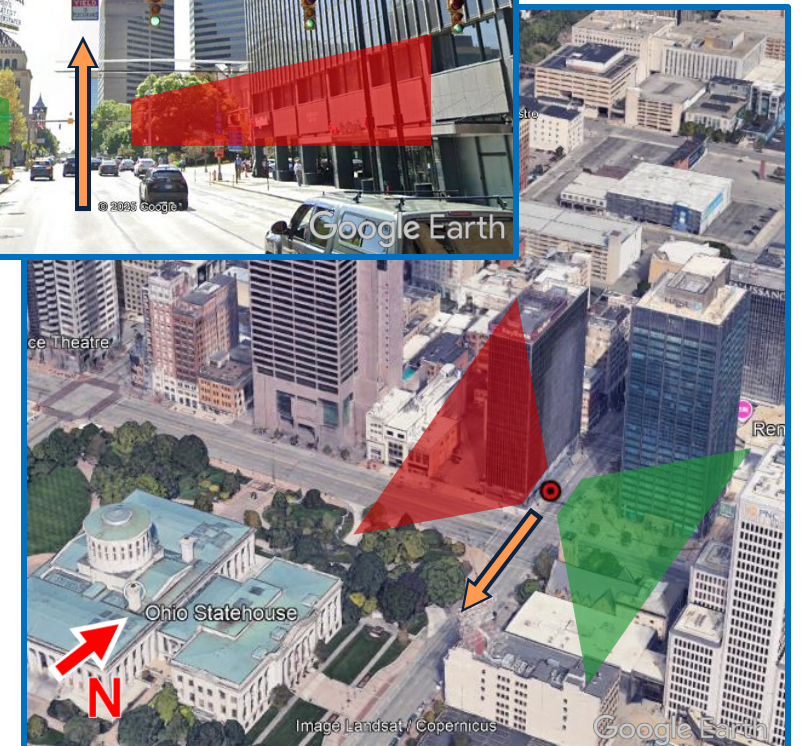
# Canyon Depth Classification



Canyon contour generated from digital elevation map data [3]



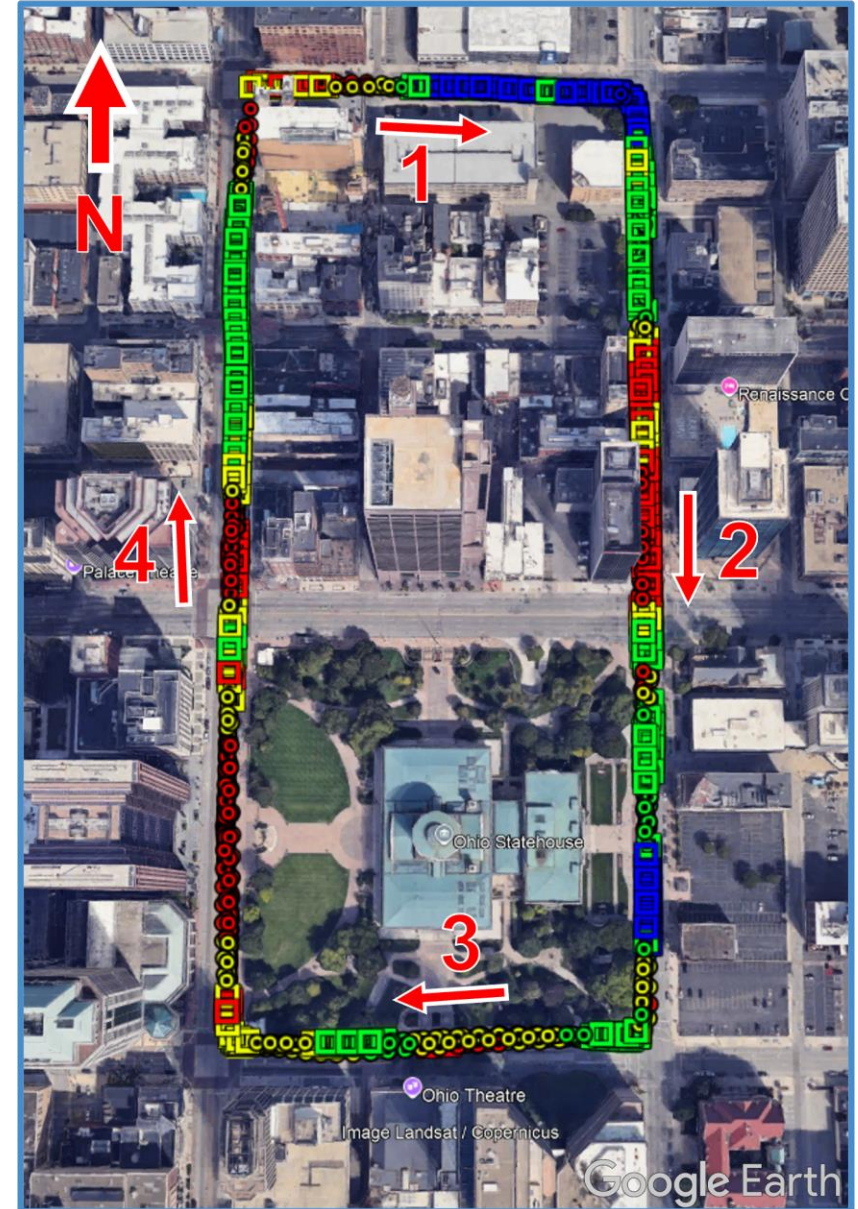
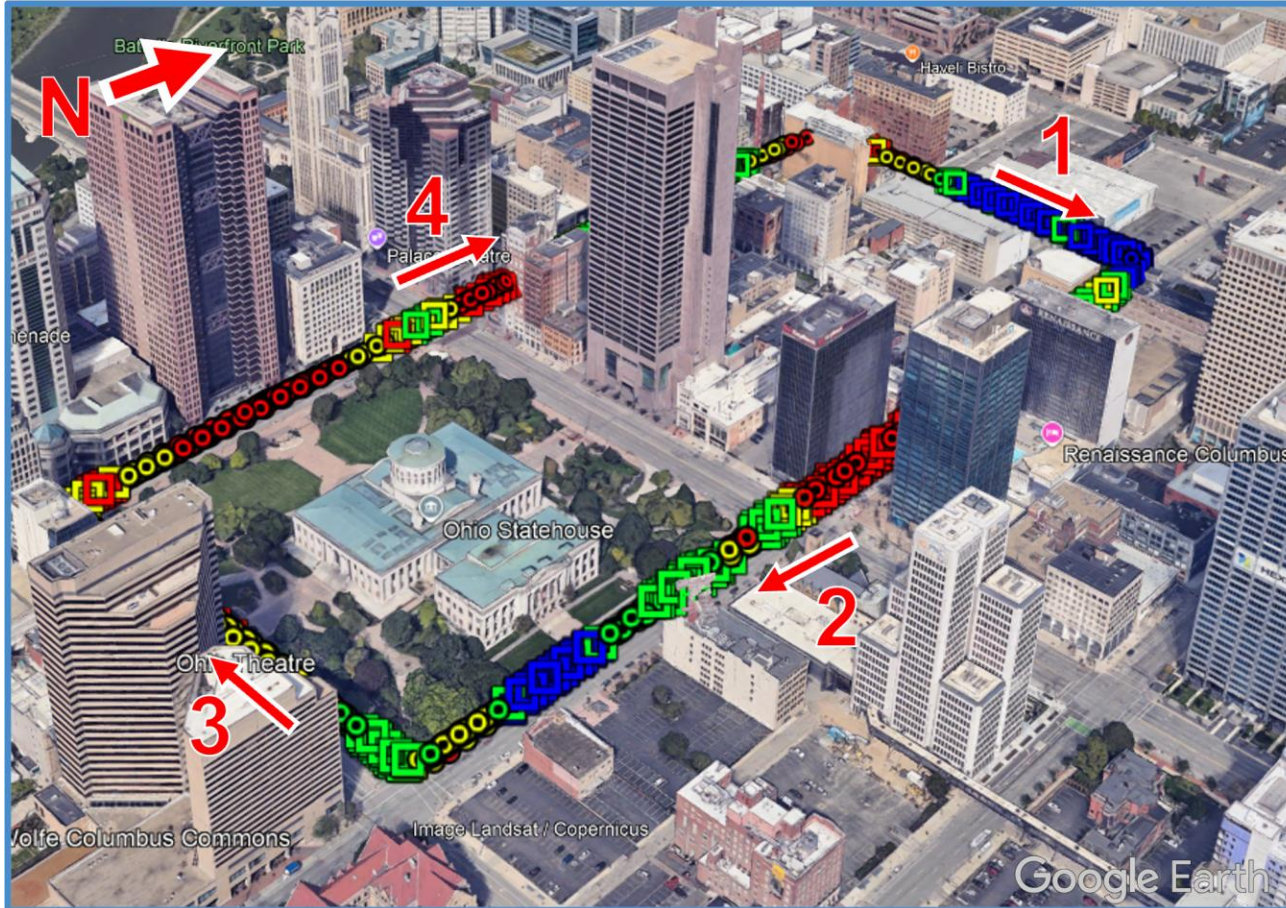
Orange arrow:  
direction of  
vehicle travel



# Urban Dataset

- Square Icons: Two-sided Canyon
- Circle Icons: One-sided Canyon

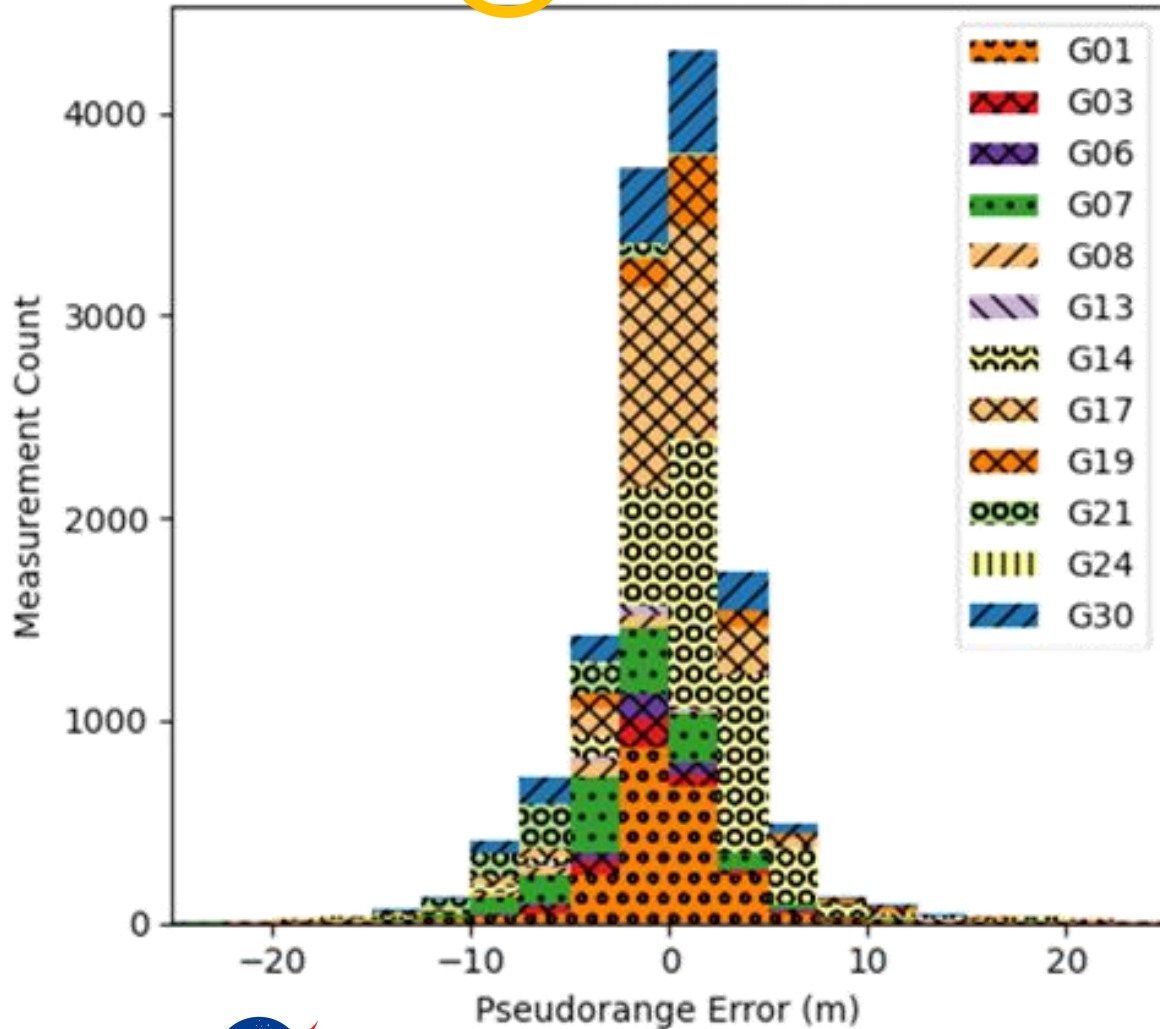
Red: Deep  
Yellow: Moderate  
Green: Shallow  
Blue: Open



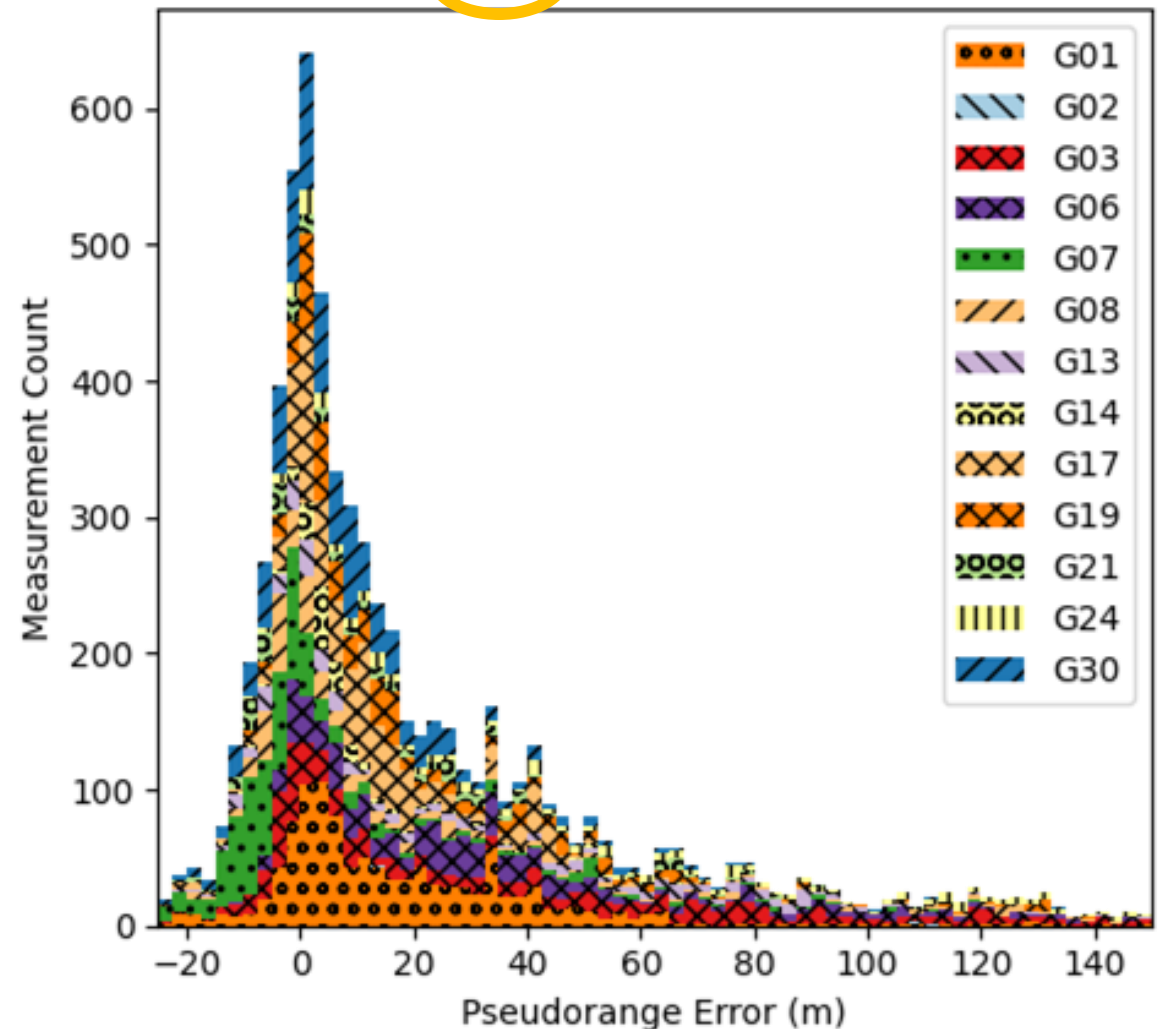
# Results

Histograms of pseudorange errors have different shapes and orders of magnitude for LOS measurements compared to NLOS measurements.

LOS Measurements



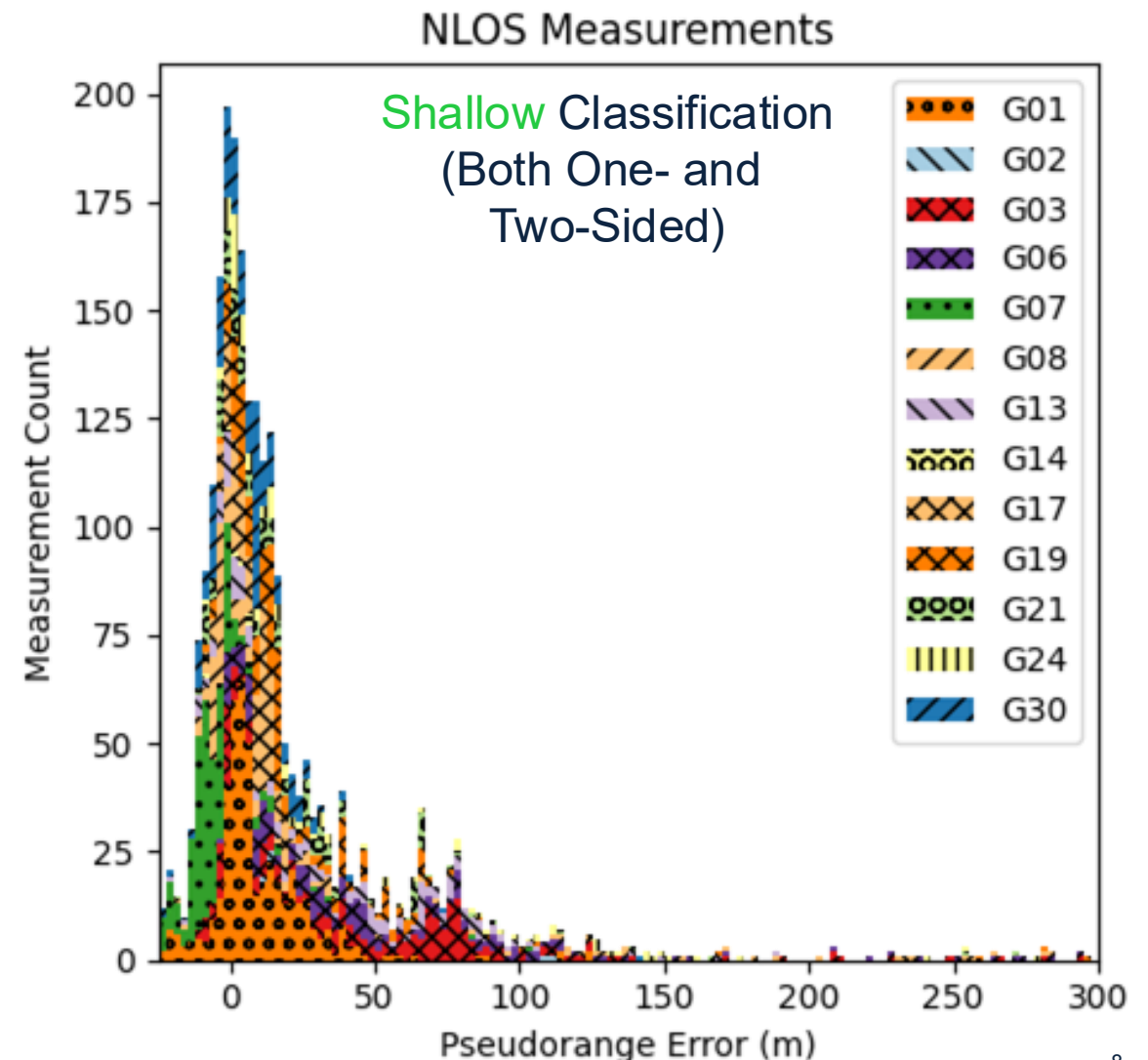
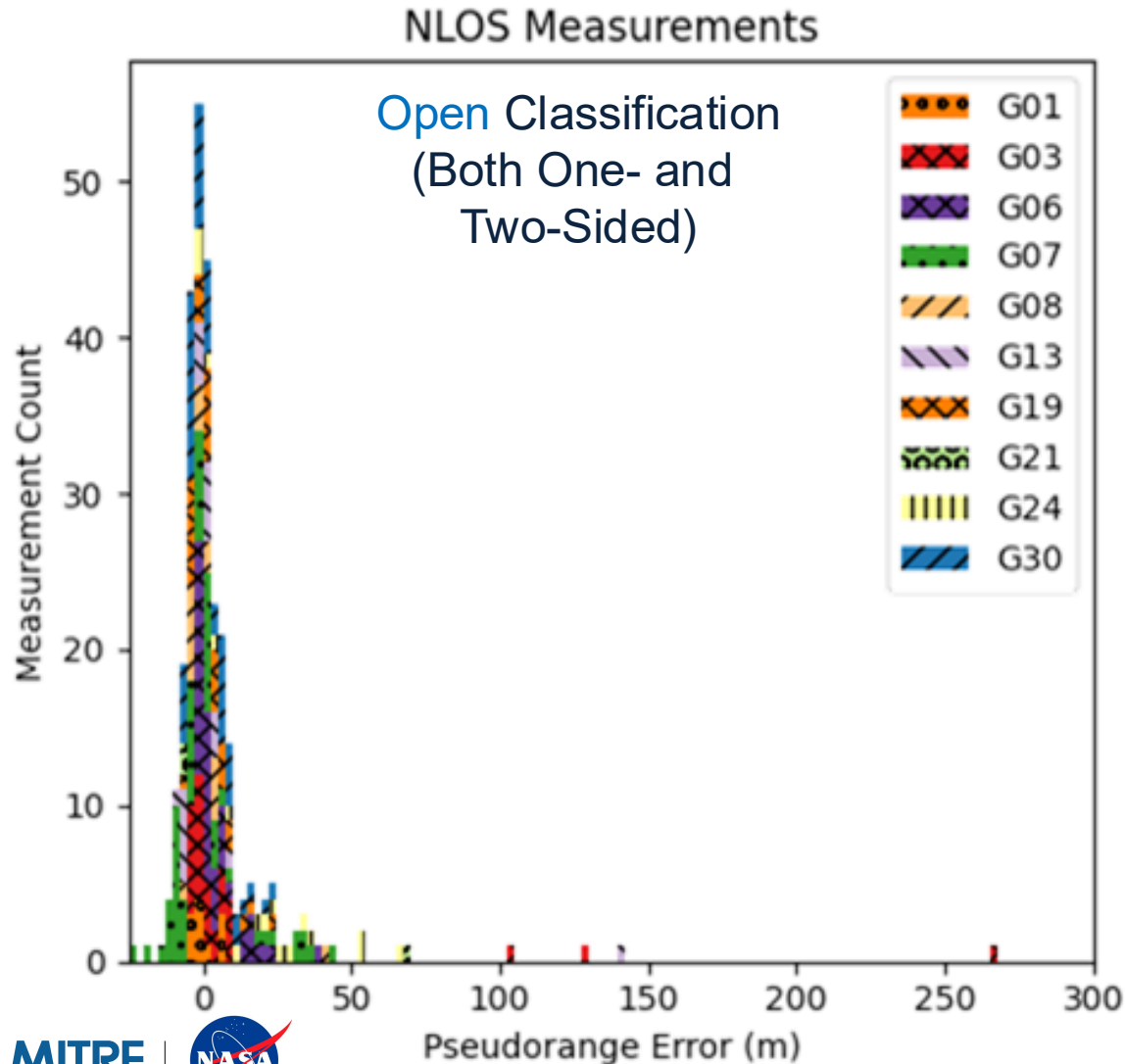
NLOS Measurements



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

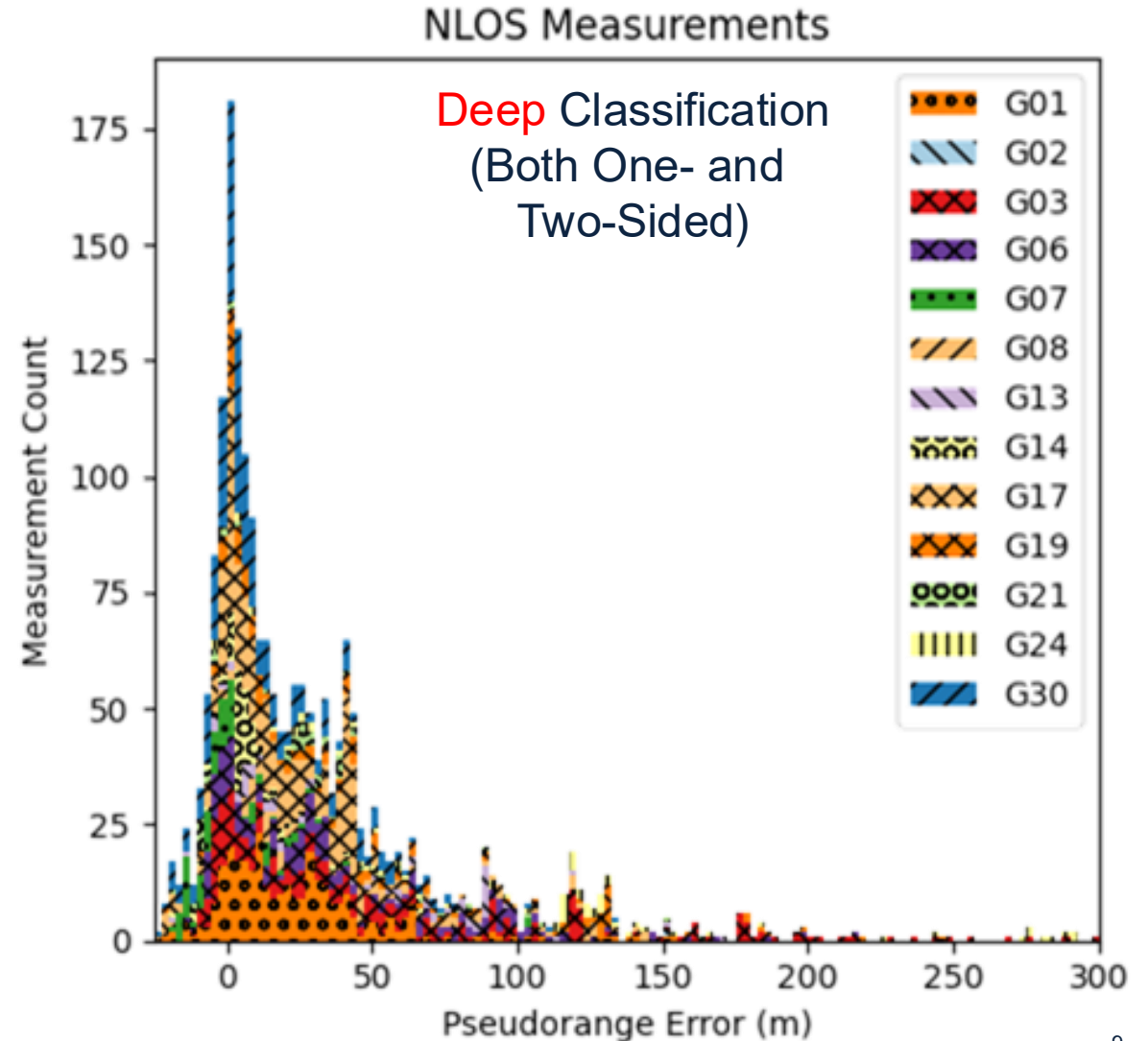
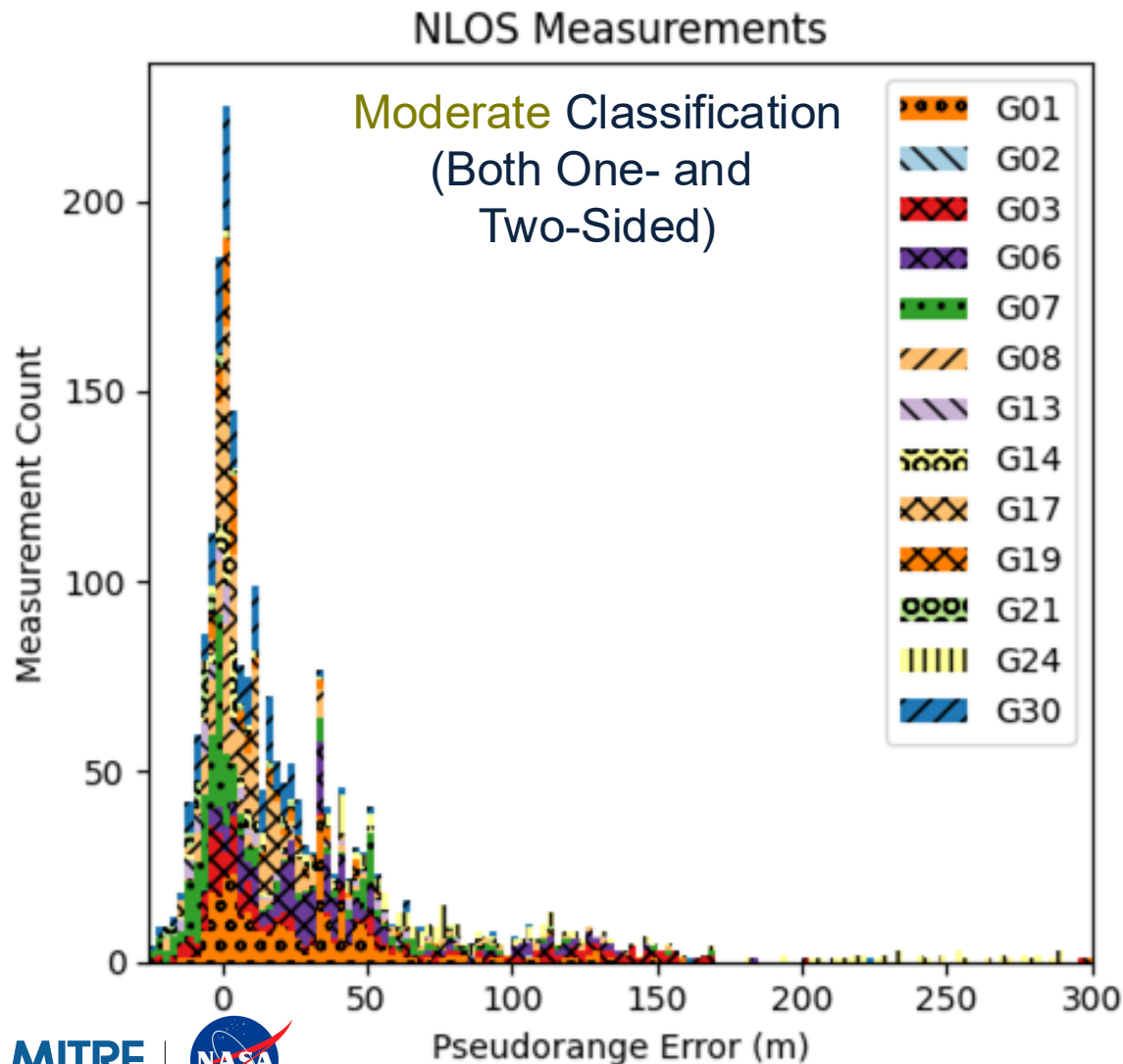
# Results

The tails of the distributions of NLOS pseudorange measurements become heavier and longer as canyon depth increases.



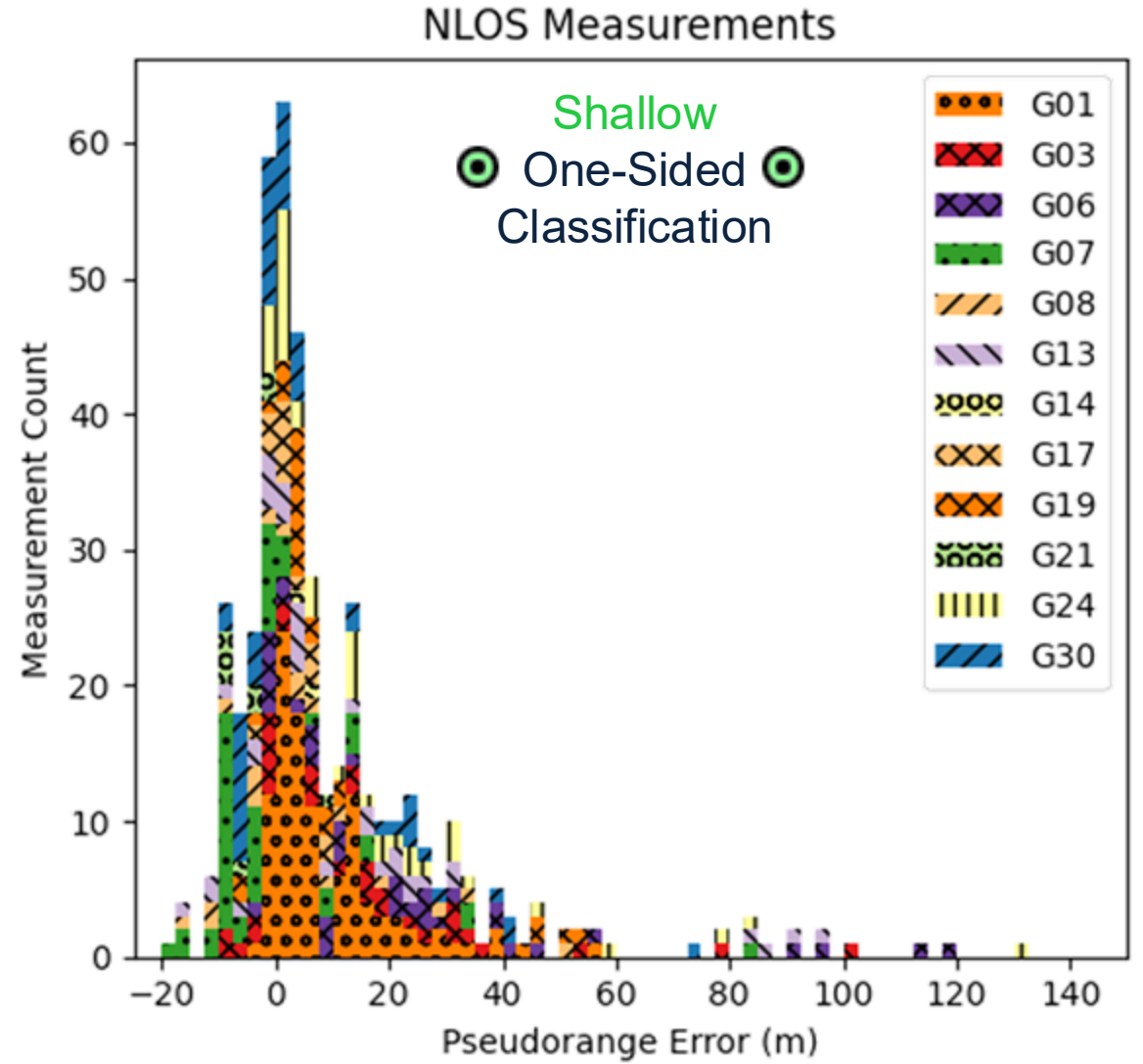
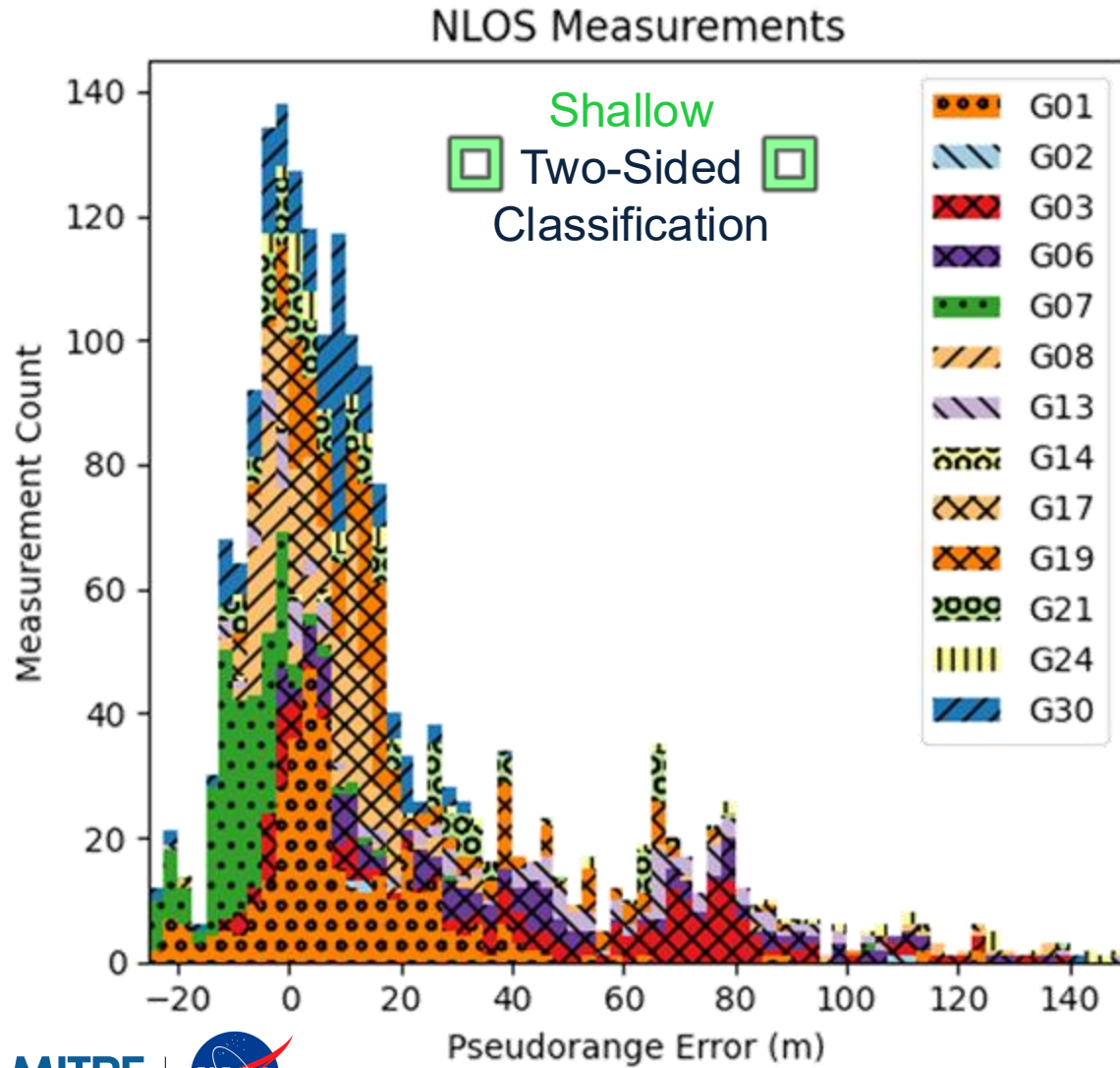
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The tails of the distributions of NLOS pseudorange measurements become heavier and longer as canyon depth increases.



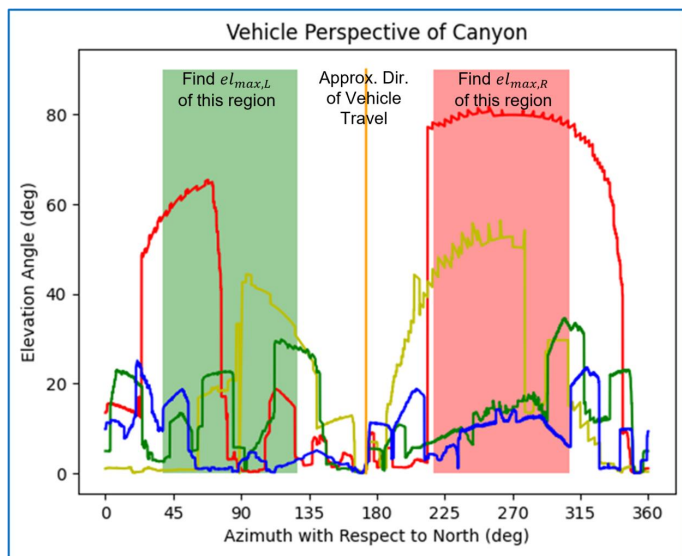
# Results

The tails of the distributions of NLOS pseudorange measurements are heavier and longer “Two-Sided” canyons compared to “One-Sided” canyons.



# Conclusions

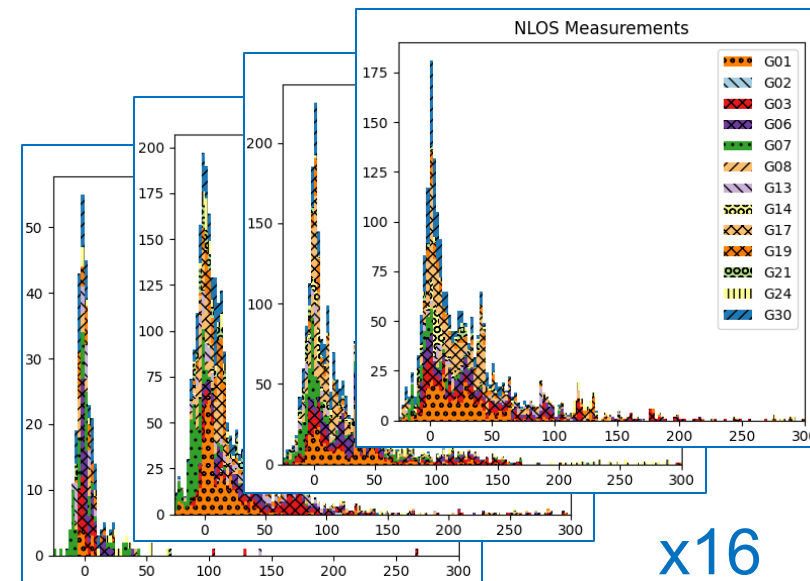
## Canyon Classification Methodology



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
- ⊙ Circle Icons: One-sided Canyon

## Empirical Pseudorange Error Distributions



Work Summary

Applications

Motivating GNSS navigation performance assessment research

- GNSS receiver integrity methods for urban environments
- Impact of receiver architecture on errors

Informing GNSS user equipment development

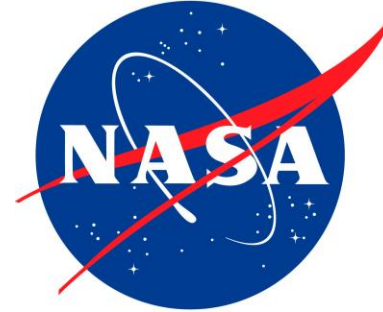
- Urban navigation tolerant tracking algorithms
- Measurement outlier rejection techniques
- Navigation filters modeling non-Gaussian errors



# References

- [1] Brooks, R. A., et al., "GPS Error Budgets, Accuracy, and Applications Considerations for Test and Training Ranges," prepared by Federal Electric Corporation for the Western Space and Missile Center (XRQ), Vandenberg AFB, California, USA, Dec. 1982.
- [2] E. R. Matera, A. Garcia-Pena, O. Julien, C. Milner, and B. Ekambi, "Characterization of Line-of-sight and Non-line-of-sight Pseudorange Multipath Errors in Urban Environment for GPS and Galileo," in Proc. 2019 Int. Tech. Meeting Inst. Navigation, Reston, VA, USA, Jan. 2019, pp. 177-196.
- [3] J. Gutierrez et al., "A High-Performance Computing Predictive GNSS Performance Monitor for Autonomous Air Vehicles in Urban Environments," NASA Langley Research Center, Hampton, VA, USA, Technical Report 20240009932, Aug. 2024.
- [4] D. Imel, "Evaluation of the TOPEX/POSEIDON dual-frequency ionosphere correction," Journal of Geophysical Research: Atmospheres, vol. 99, 1995. doi: 10.1029/94JC01869.
- [5] P. Misra and P. Enge, Global Positioning System: Signals, Measurements, and Performance, Revised 2nd ed. Lincoln, MA, USA: Ganga-Jamuna Press, 2011.
- [6] Brocard, P.-A., "Improving the accuracy of GNSS-based ionospheric tomography: Application to the monitoring of mid-latitude ionospheric structures," Ph.D. dissertation, Univ. Toulouse, Toulouse, France, 2016. Available: <https://theses.hal.science/tel-01379632/file/Brocard.pdf>

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# Questions?

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<sup>1</sup> The MITRE Corporation

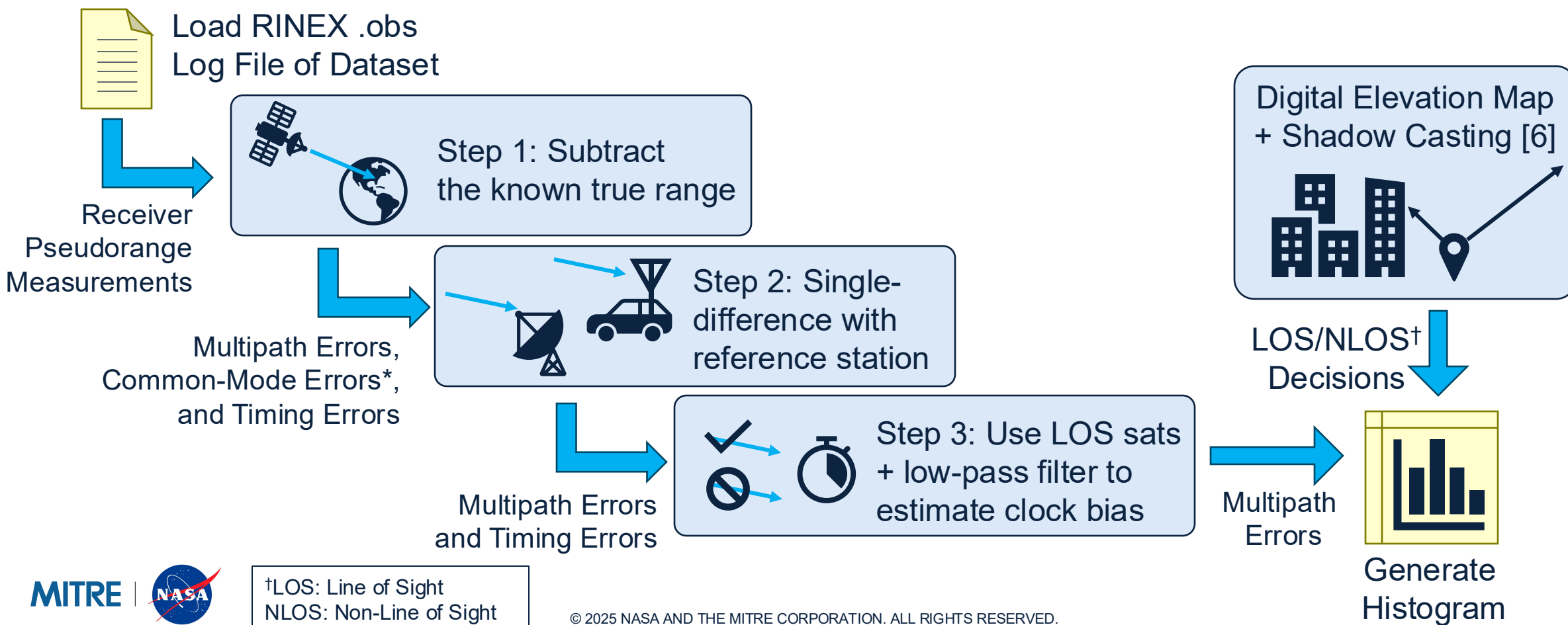
<sup>2</sup> NASA Langley Research Center

# Backup

# 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.



<sup>†</sup>LOS: Line of Sight  
NLOS: Non-Line of Sight

# Canyon Depth Classification

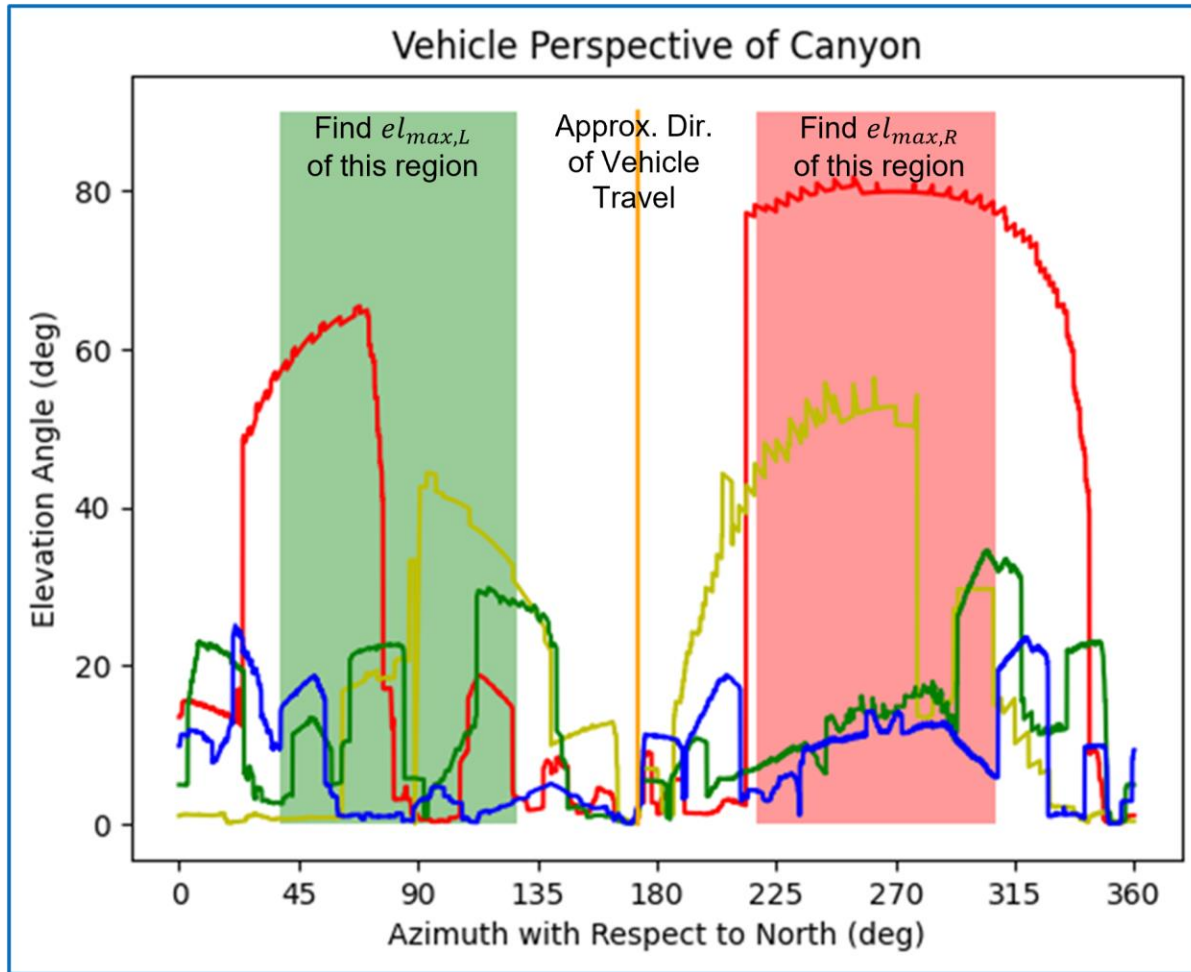


TABLE I: Urban Canyon Classification

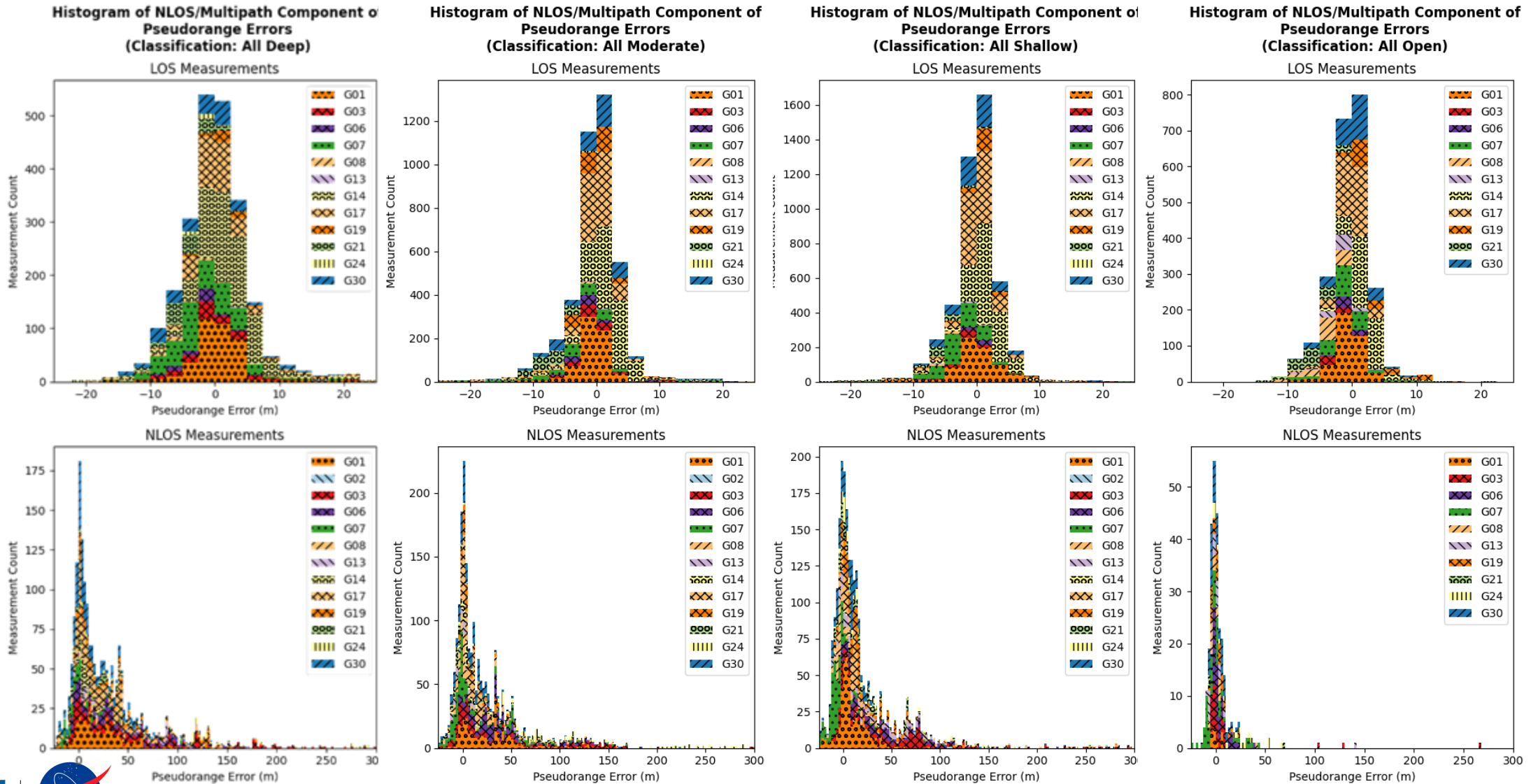
Urban Canyon Depth Characterization Label	Max Elevation Angle to Top of Building on Deeper Side of Canyon	Map Icon Color
Open	0 to 30°	Blue
Shallow	30° to 55°	Green
Moderate	55° to 70°	Yellow
Deep	70° to 90°	Red

“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”

# Results

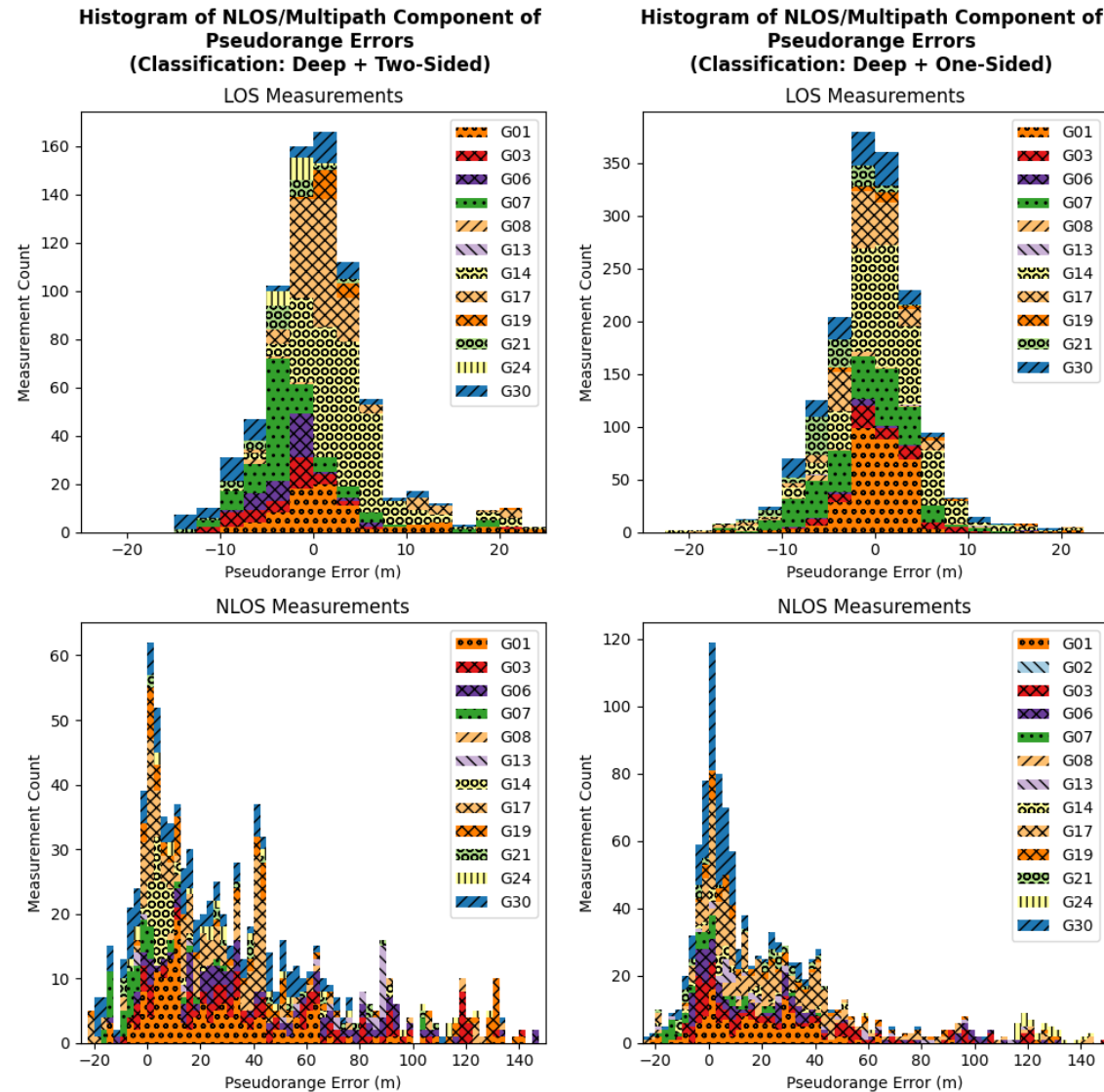
Distributions formed from NLOS measurements change more than distributions formed from LOS measurements as canyon depth changes.



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

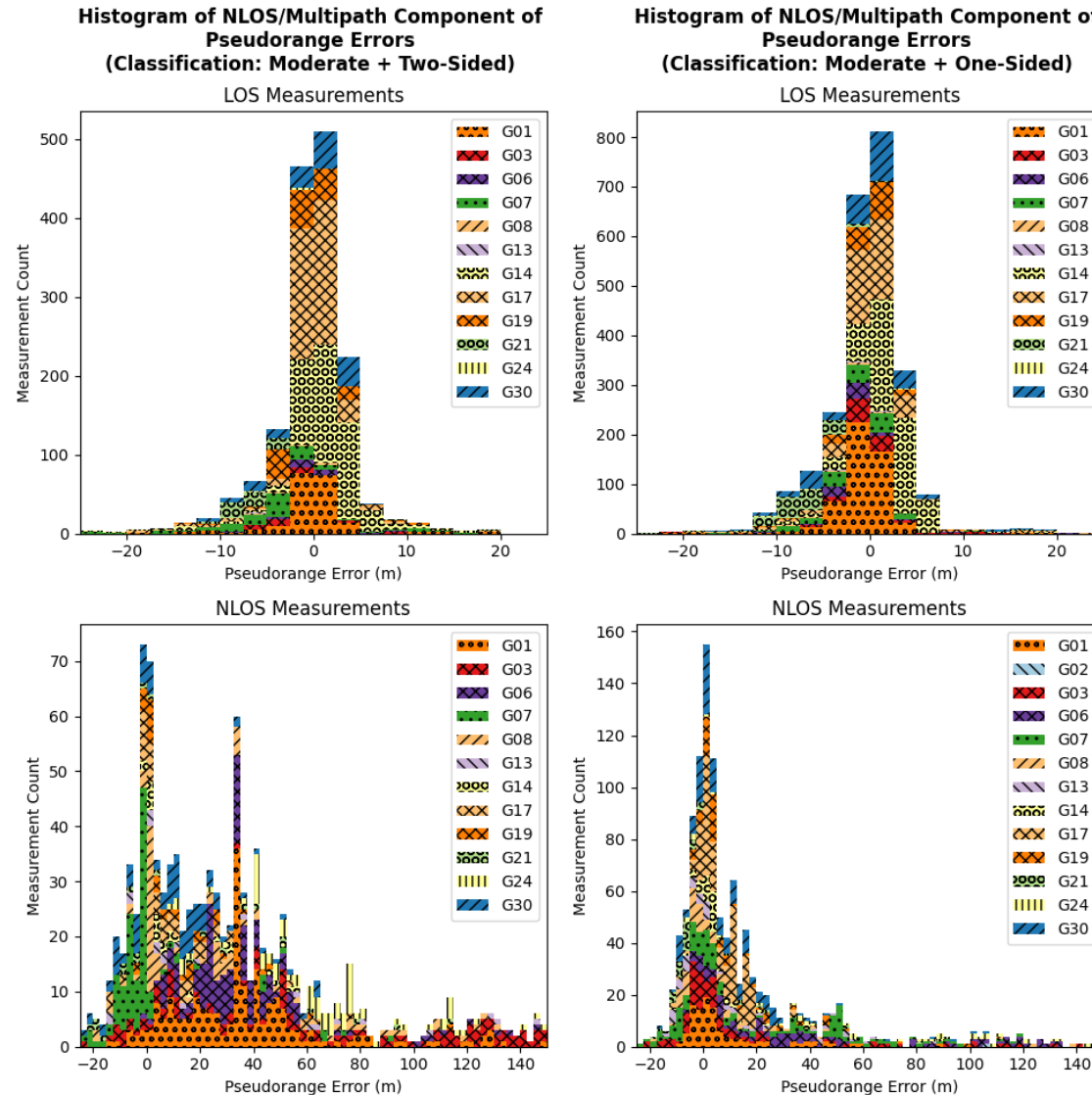
# Results

Tails are heavier and longer in distributions formed from canyons classified “Deep + Two-Sided” compared to canyons classified “Deep + One-Sided”.



# Results

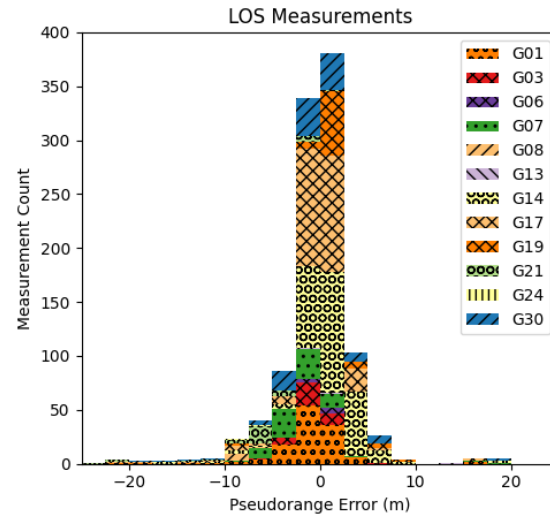
Tails are heavier and longer in distributions formed from canyons classified “Moderate + Two-Sided” vs canyons classified “Moderate + One-Sided”.



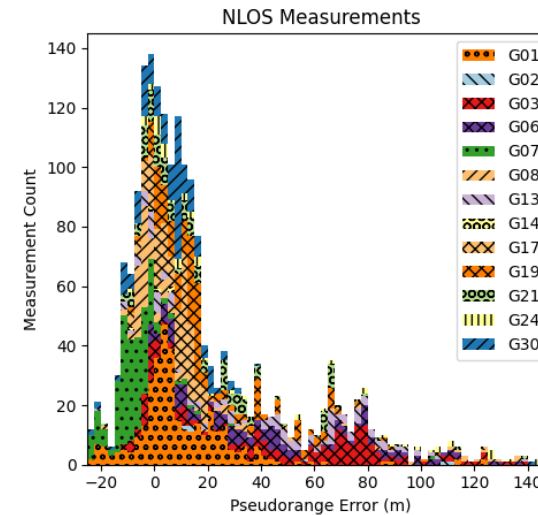
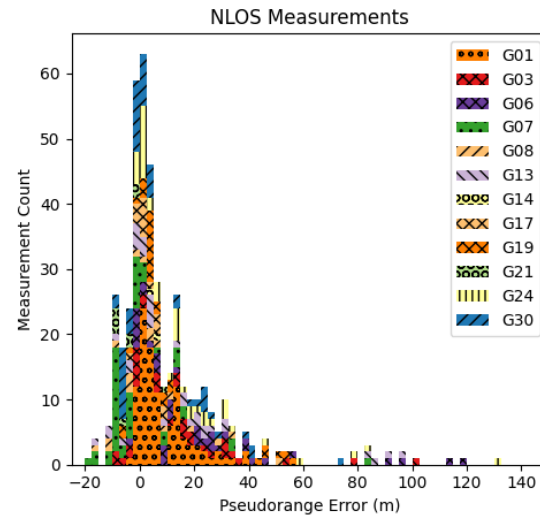
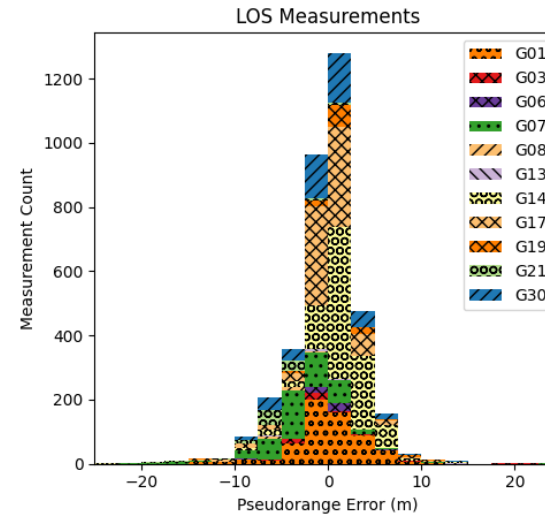
# Results

Tails are heavier and longer in distributions formed from canyons classified “Shallow + Two-Sided” vs canyons classified “Shallow + One-Sided”.

Histogram of NLOS/Multipath Component of Pseudorange Errors (Classification: Shallow + One-Sided)

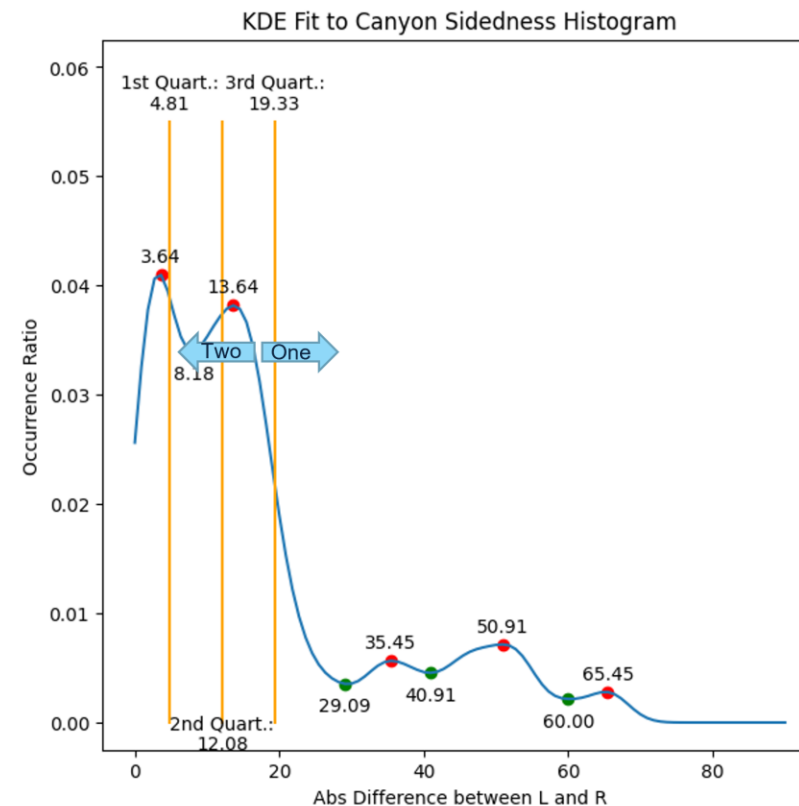
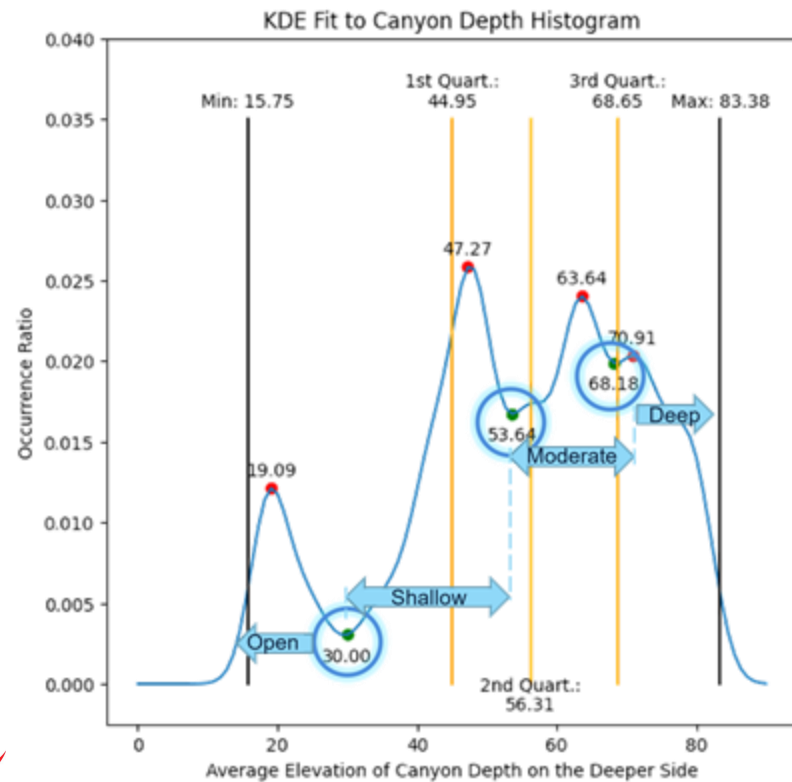


Histogram of NLOS/Multipath Component of Pseudorange Errors (Classification: Shallow + Two-Sided)



# Choosing Classification Thresholds

- Thresholds for canyon depth were chosen near local minima of a plot of the frequency of canyon elevation.
- The threshold for classifying “One-Sided” vs “Two-Sided” was chosen slightly past a local maximum of the frequency of absolute difference of canyon heights.



# Conclusions

## Work provides:

- Methodology for empirical study of pseudorange errors from multipath and NLOS
  - Proposed classifiers for canyon depth and “sided-ness”
  - Proposed scheme for segmenting city based on urban canyon features to generalize error analysis
- Empirical distributions for errors in 16 different urban canyon classes

## Applications:

- Informing research and development, including:
  - Tracking loop designs
  - Navigation filters
  - Receiver integrity techniques
- Validating analytical and modeling & simulation techniques