# Deep Learning-Based Multipath Detection in GNSS Signals

Using Delay-Doppler Correlation Maps and CNN Classification

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# 01
# Introduction

GNSS Multipath Problem & Motivation

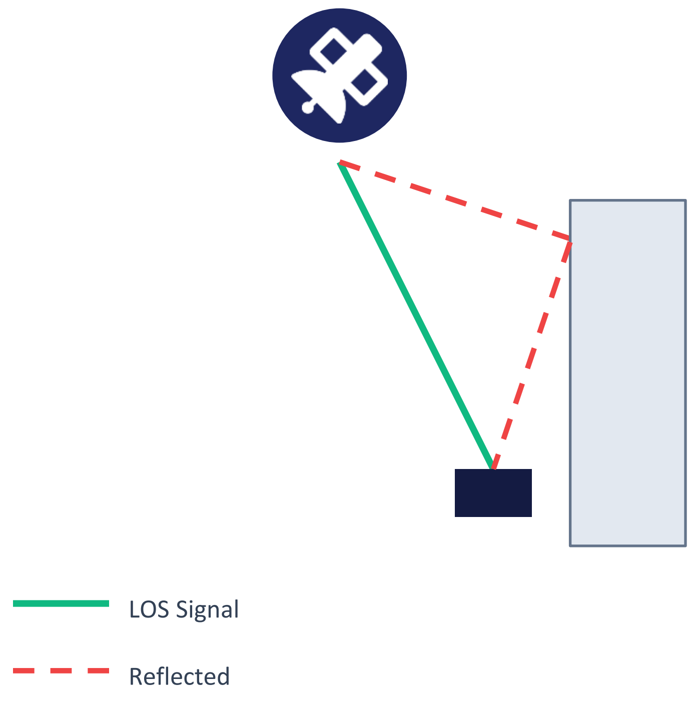
# GNSS Multipath Problem

## Urban Challenge

**Signal Reflections**
Signals bounce off buildings, vehicles, and terrain before reaching the receiver

**Correlation Distortion**
Multiple signal paths distort the correlation function used for ranging

**Position Errors**
Pseudorange errors can reach tens of meters in severe conditions



# Multipath Signal Model

## Received Signal Model

$$r(t) = s(t) + \sum \alpha_k \cdot s(t - \tau_k) \cdot e^{j(2\pi f_{d,k} t + \phi_k)} + n(t)$$

*LOS signal + K multipath reflections + noise*

### $\alpha_k$

Amplitude ratio

**[-20, -3] dB**

### $\tau_k$

Path delay

**10-300 m**

### $f_{d,k}$

Doppler offset

**Variable Hz**

### $\phi_k$

Phase offset

**[0, 2π]**

Key Insight: If we can estimate α, τ, and phase relationship, we can correct the pseudorange measurement

02

# Methodology

Correlation Maps & CNN Classification

# End-to-End Processing Pipeline

**RF Reception** → **IQ Sampling** → **PRN Correlation** → **Delay-Doppler Map** → **CNN Classification** → **Position Solution**

| RF Reception | IQ Sampling | PRN Correlation | Delay-Doppler Map | CNN Classification | Position Solution |
|---|---|---|---|---|---|
| Antenna | 16.368 MHz | FFT | 64×64 | ResNet-18 | WLS |

Signal Acquisition | Feature Extraction | Deep Learning & Output

Novel contribution: 2D Delay-Doppler maps as standardized CNN input → enables transfer learning across receivers

# Delay-Doppler Correlation Maps

## Correlation Function

$$R(\tau, f^d) = \left|\sum r[n] \cdot c^*[n-\tau] \cdot e^{(-j2\pi f^d n T_s)}\right|^2$$

**τ** spans code delay search range
**$f^d$** spans Doppler frequency range
**Result:**
64×64 2D image capturing signal characteristics

## Correlation Map Examples

| | |
|---|---|
| **Clean** | **Weak MP** |
| **Severe MP** | **NLOS** |

## Four-Class Severity Classification

| Class 0 | Class 1 | Class 2 | Class 3 |
|---|---|---|---|
| **CLEAN** | **LOS_WITH_MP** | **SEVERE_MP** | **NLOS** |
| No multipath | Weak ($\alpha < -10$ dB) | Strong ($\alpha > -6$ dB) | LOS blocked |

03

# CNN Architecture

Network Design & Training Strategy

# CNN Architectures Evaluated

### SimpleCNN

**2.2M**
parameters

3-layer baseline with batch norm

### ResNet-18

**11.2M**
parameters

Skip connections for deep learning

★ BEST

### VGG-Small

**2.5M**
parameters

Sequential 3×3 convolutions

### ShallowConv

**47K**
parameters

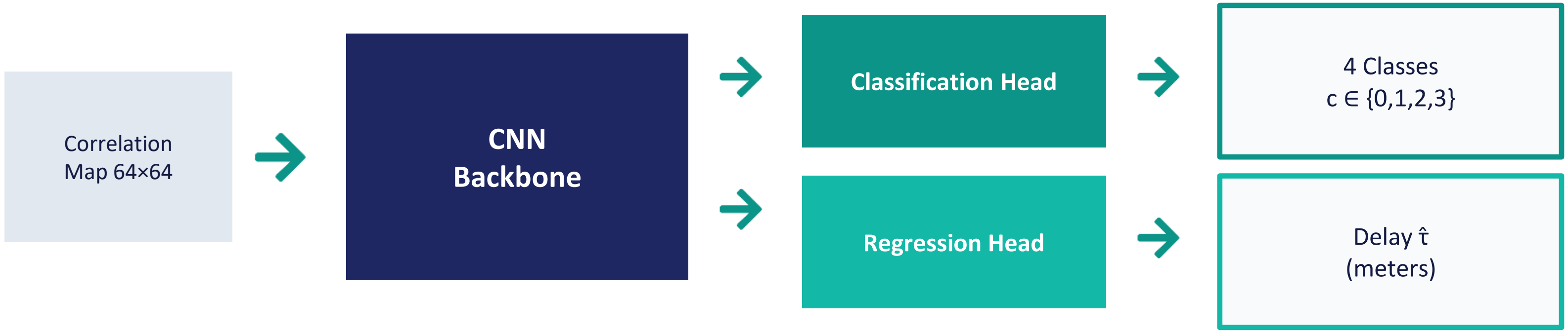
Minimal 2-layer lightweight

## ResNet-18: Residual Learning

$$y = F(x, \{W_i\}) + x$$

**Skip connections** allow gradients to flow directly through the network, mitigating vanishing gradient problem and enabling deeper feature extraction.

# MultipathEstimator: Joint Classification & Regression




### Multi-task Loss

$$L = L_{cls} + \lambda_{reg} \cdot L_{reg} + \lambda_{conf} \cdot L_{conf}$$

Weighted cross-entropy + MSE regression

### Pseudorange Correction

$$\Delta\rho = \alpha_c \cdot \min(\hat{\tau}, 30m) \cdot \gamma$$

$\rho' = \rho - \Delta\rho$ (corrected pseudorange)

# 04
# Experimental Results

Classification & Position Accuracy

# Dataset & Training Configuration

## Dataset

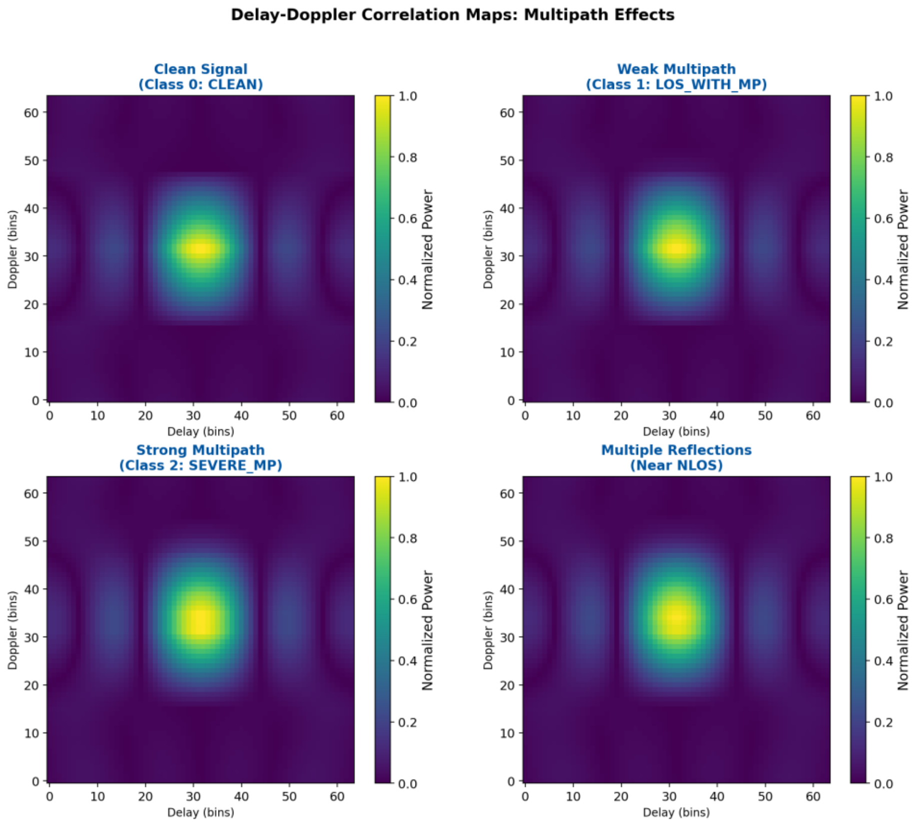
- GPS L1 C/A signals (PRN 1-5)
- Sampling: 16.368 MHz
- Map resolution: 64×64
- SNR: 35-45 dB-Hz
- 10,000 total samples
- Train/Val/Test: 70/15/15%

## Training

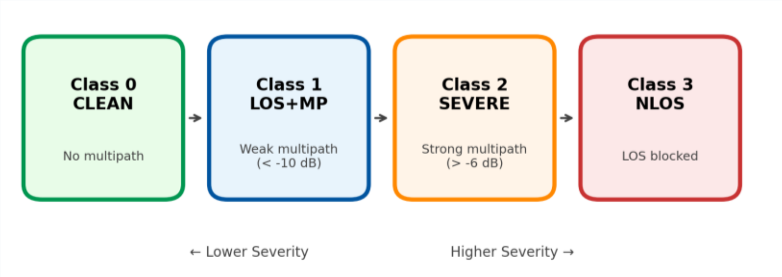
- Optimizer: AdamW
- Learning rate: $10^{-3}$ (cosine)
- Batch size: 64
- Early stopping: 10 epochs
- Mixed precision (FP16)
- Hardware: RTX A4000

Class Distribution: 25% Clean | 75% Multipath (distributed across severity levels)

# Multipath

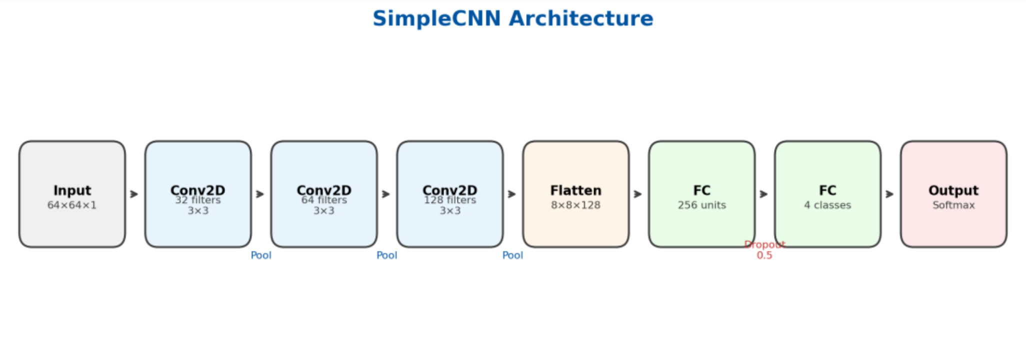


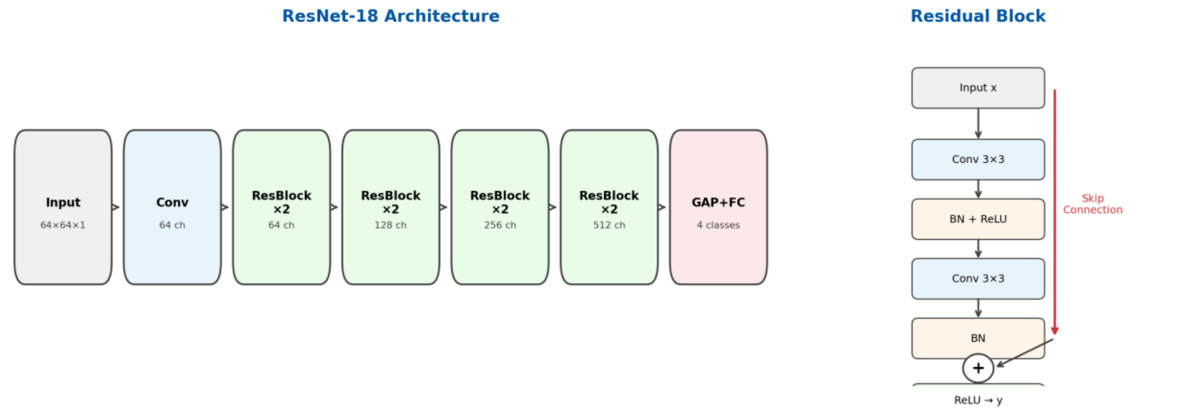
Delay-Doppler Correlation Maps: Multipath Effects
Clean Signal
(Class 0: CLEAN)
Weak Multipath
(Class 1: LOS_WITH_MP)
Strong Multipath
(Class 2: SEVERE_MP)
Multiple Reflections
(Near NLOS)
Doppler (bins)
Delay (bins)
Normalized Power

Class 0
CLEAN
No multipath
Class 1
LOS+MP
Weak multipath
(< -10 dB)
Class 2
SEVERE
Strong multipath
(> -6 dB)
Class 3
NLOS
LOS blocked
← Lower Severity
Higher Severity →

# NN Classification



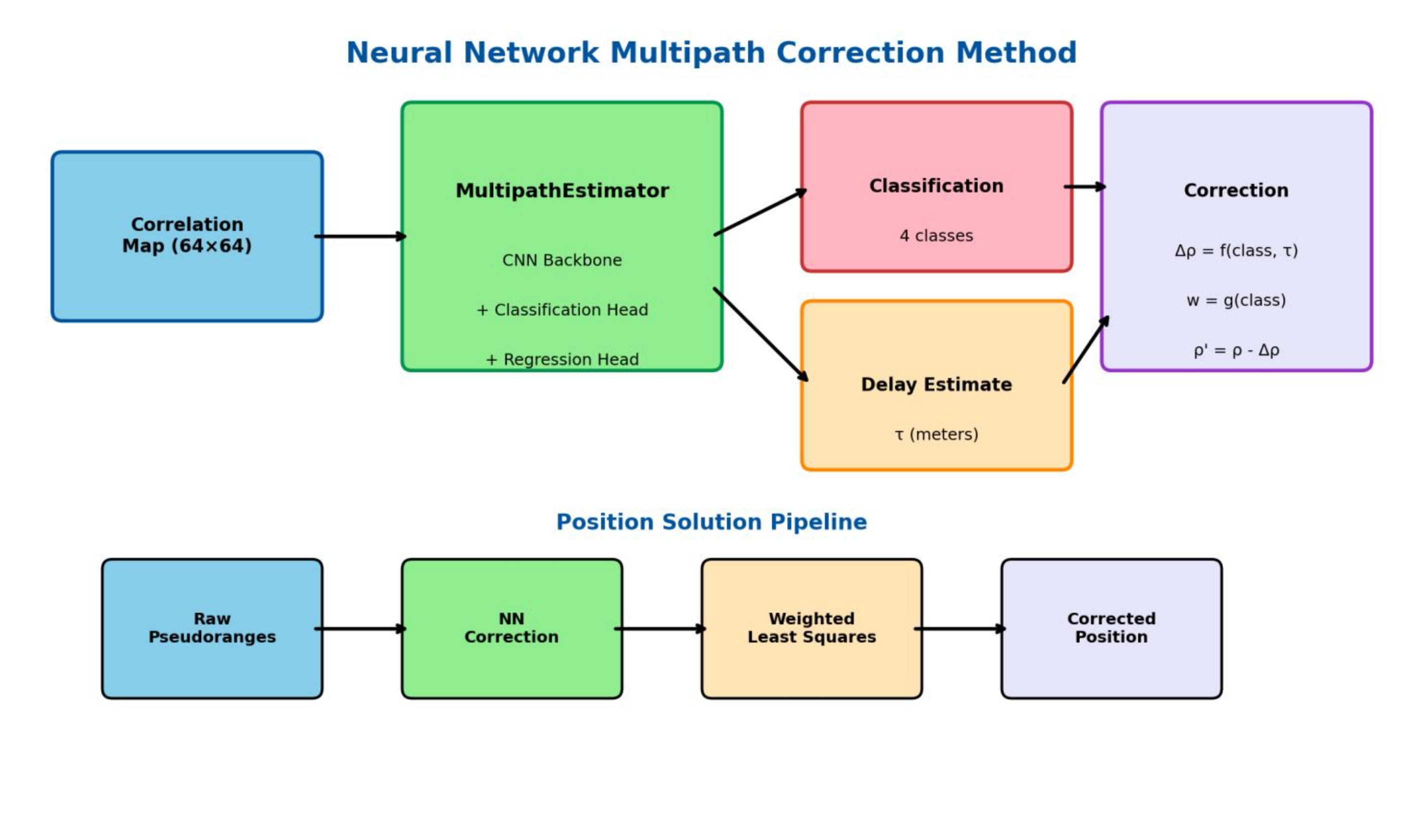
# Classification Performance Comparison

| Model | Parameters | Accuracy | F1 Macro | Precision |
| --- | --- | --- | --- | --- |
| SimpleCNN | 2.2M | 70.2% | 0.538 | 0.560 |
| **ResNet-18** | **11.2M** | **95.4%** | **0.830** | **0.768** |
| VGG-Small | 2.5M | 27.2% | 0.156 | 0.178 |
| ShallowConv | 47K | 66.9% | 0.268 | 0.241 |

## Key Findings

- ResNet-18 achieves best performance (95.4% accuracy, 0.830 F1)
- Skip connections crucial for learning correlation patterns
- VGG suffered from vanishing gradients without residual connections

# Classification Performance Comparison



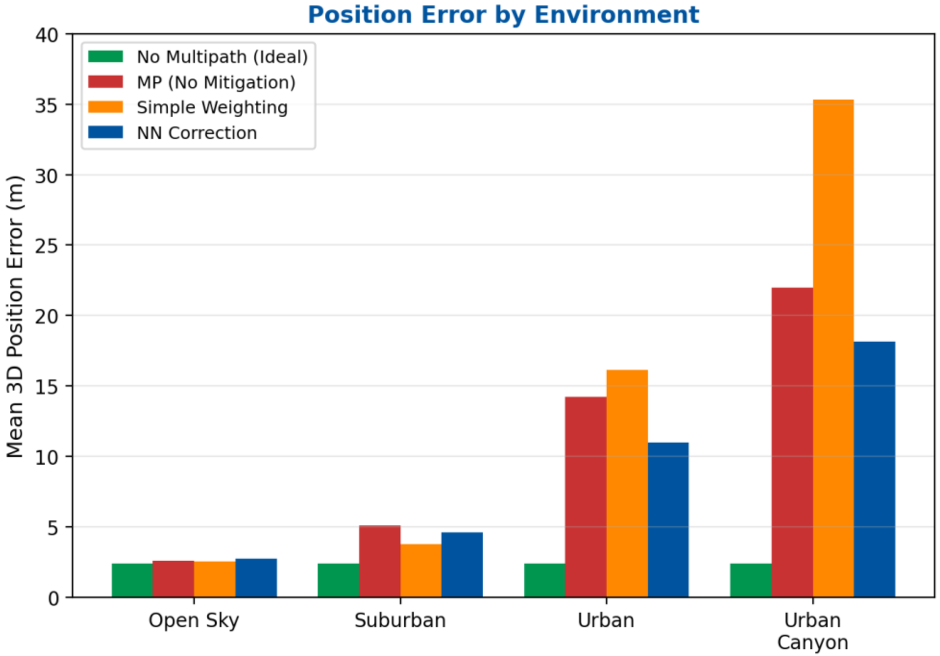
# Position Accuracy Evaluation

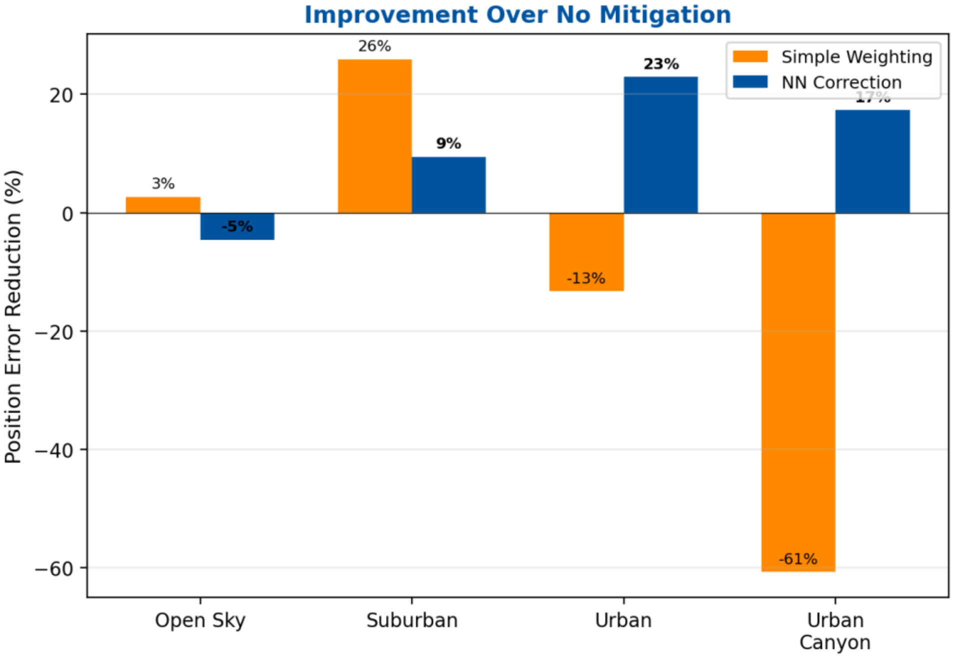
| Environment | No MP | No Mitigation | Simple | NN Corr. | Improv. |
|---|---|---|---|---|---|
| Open Sky | 2.43 m | 2.63 m | 2.56 m | 2.75 m | — |
| Suburban | 2.43 m | 5.09 m | 3.77 m | **4.61 m** | **9%** |
| Urban | 2.43 m | 14.25 m | 16.14 m | **10.98 m** | **23%** |
| Urban Canyon | 2.43 m | 21.97 m | 35.31 m | **18.16 m** | **17%** |

### Key Insight: Correction vs Exclusion

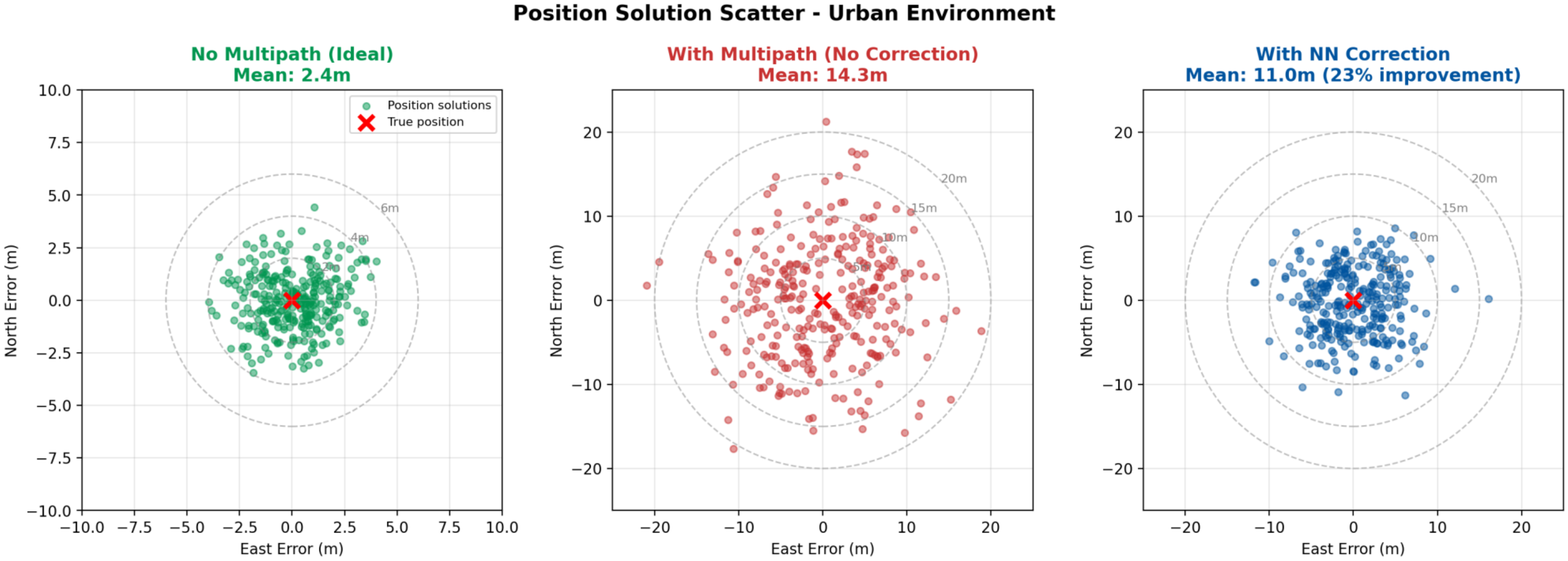
Simple weighting degrades in urban canyons because excluding satellites worsens geometry (DOP). NN correction maintains geometry by correcting measurements rather than excluding them.

# Position Accuracy Evaluation



# Position Accuracy Evaluation



# 05
# Conclusions

Summary & Future Directions

# Key Results & Contributions

**95.4%**
Classification Accuracy

**23%**
Urban Position Improvement

**17%**
Urban Canyon Improvement

**~15m**
Delay Estimation MAE

## Contributions

- Novel 2D delay-Doppler map representation for CNN-based multipath detection
- Comprehensive architecture comparison (SimpleCNN, ResNet, VGG, ShallowConv)
- Joint classification-regression model enabling pseudorange correction
- Proof that correction outperforms exclusion by preserving satellite geometry

# Future Directions

### Real-World Validation

Test on actual GNSS receiver data from urban environments

### Multi-Constellation

Extend to GPS + Galileo + BeiDou integration

### Real-Time Deployment

Optimize for embedded GNSS receiver implementation

### Carrier Phase

Extend to carrier phase multipath for high-precision applications

# Thank You!

## Questions?

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