

Scalable Wireless Digital Twins and ML Models for High-Fidelity RF Signal Mapping

Tingjun Chen

Nortel Networks Assistant Professor

Pierre R. Lamond Department of Electrical and Computer Engineering

Duke University

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RF Propagation Models for Wireless Digital Twins (DTs)

Analytical/empirical models

- Easy to compute
- No site-specific information

Examples:

- Friis free space path gain model
- 3GPP models (e.g., UMa, UMi)
- Ericsson model
- ...

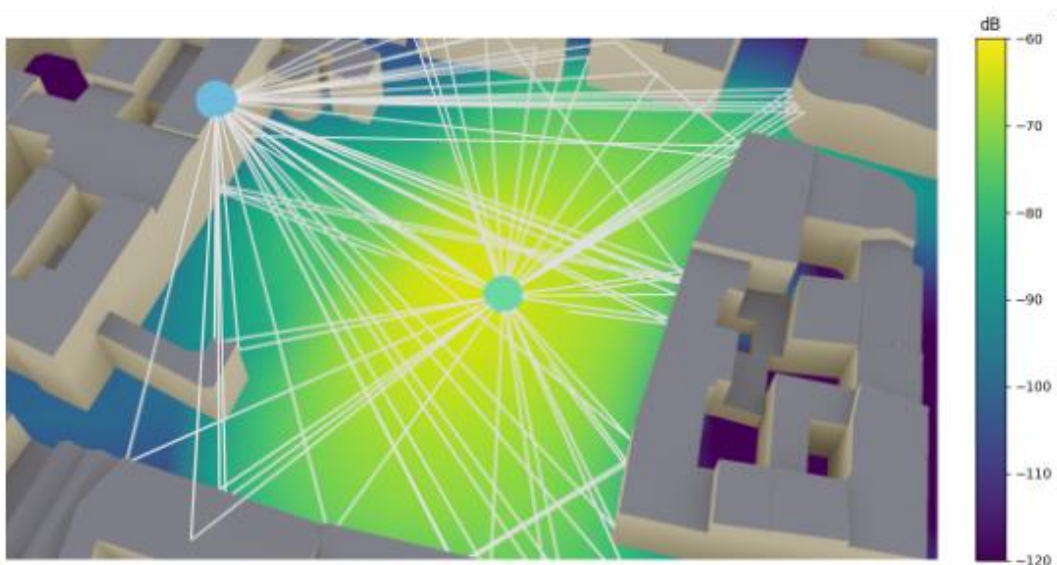
Model	Equations
Ericsson	$PL_E = a_0 + a_1 \log_{10}(d) + a_2 \log_{10} h_{Rx} + a_3 \log_{10} h_{Tx} \log_{10}(d) - 3.2(\log_{10} 11.75 h_{Rx})^2 + g(f) \quad (1)$ $g(f) = 44.49 \log_{10}(f) - 4.78(\log_{10}(f))^2 \quad (2)$
Free Space	$PL_{FSPL} = 32.45 + 20 \log(d) + 20 \log_{10}(f) \quad (3)$

Ray tracing (RT) models

- More computationally expensive
- Site- and radio-specific

Examples:

- Altair WinProp  **ALTAIR**
- Wireless InSite  **REMCOM**
- SIRADEL Volcano  **SIRADEL**
- MATLAB  **MathWorks**
- Sionna* RT/PHY/SYS  **NVIDIA**
*open-source



ML-based models

- Fast inference (potentially)
- Site- and radio-specific

→ Trained on **synthetic** data

→ Tested on **synthetic** data

Unrealistic



1. Scalable 3D scene generation

2. Scalable ML models for RF signal mapping

→ Trained on **measurement** data

→ Tested on **measurement** data

Requires substantial measurements

Geo2SigMap: Tools, Datasets, and Tutorials

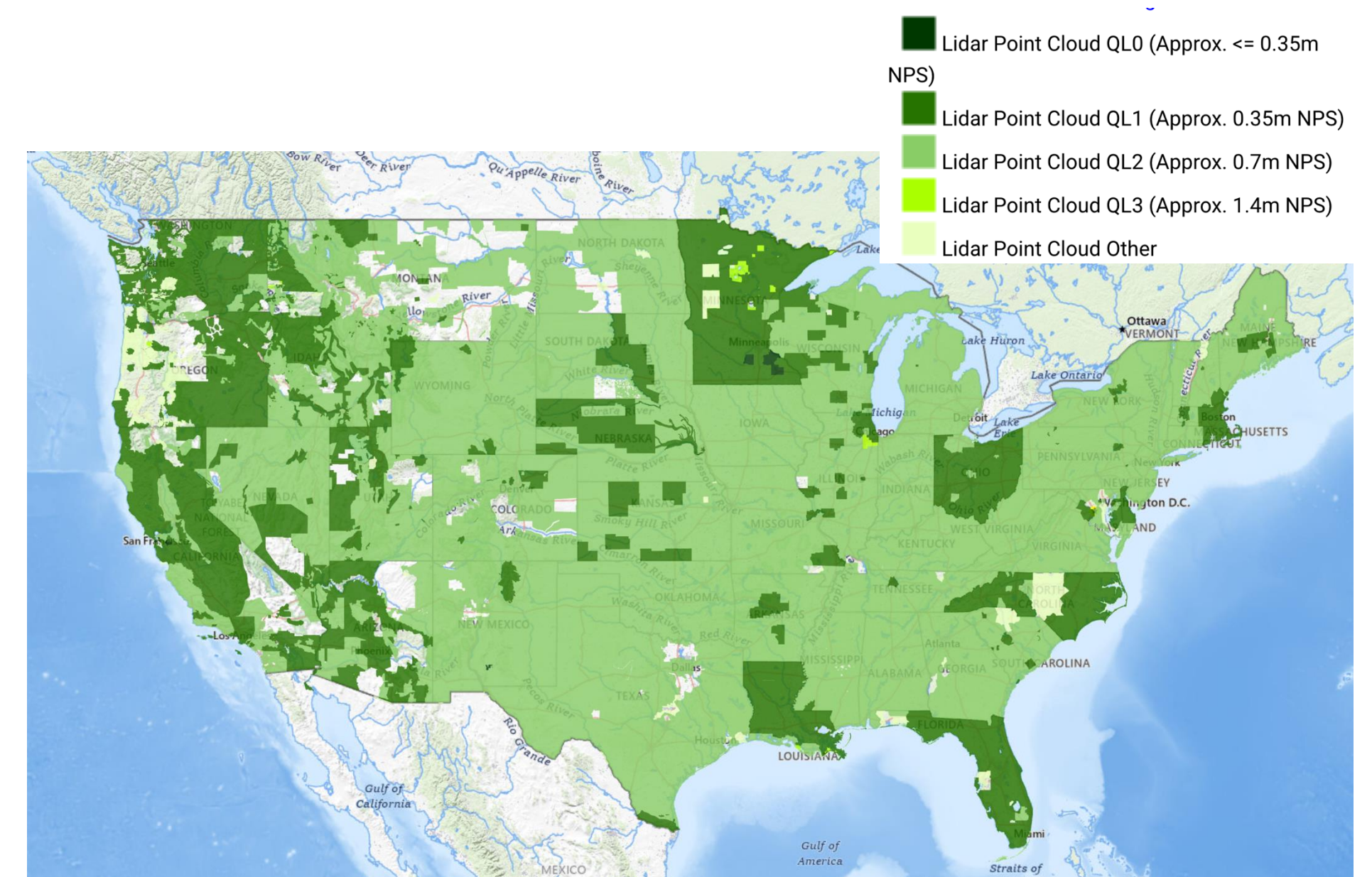
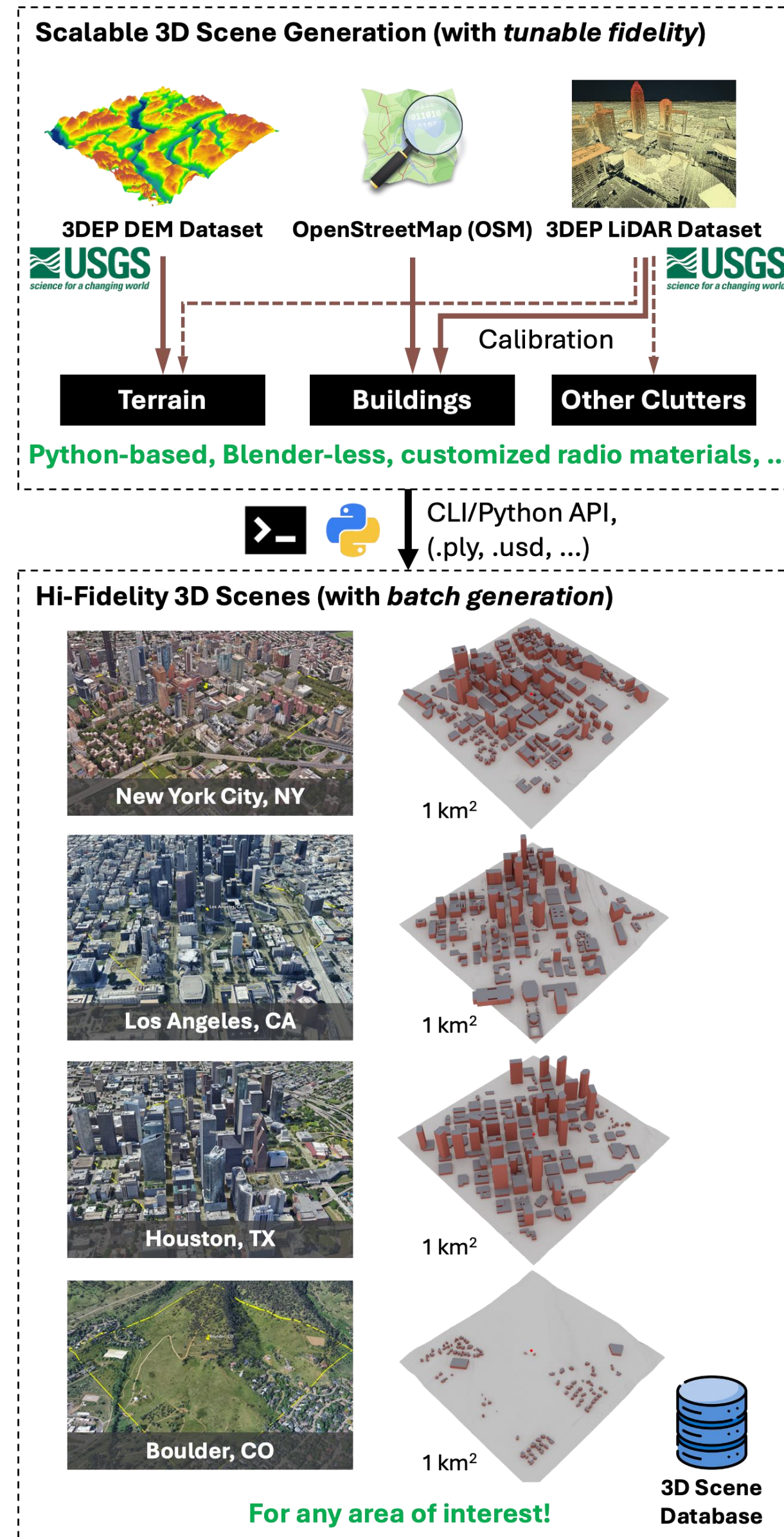
- **v1.0 (*Spring 2025*): The *first* fully open-sourced, scalable pipeline for building wireless DTs**
 - CLI tool + Python API for 3D scene generation of *arbitrary areas of interest*
 - *Seamless integration* of the generated 3D scenes with NVIDIA's Sionna RT and AODT
 - Downstream tasks: comparison with real-world measurements, integration with deep learning models, ...
 - Accompanied with a suite of Jupyter Lab based *examples and tutorials*

>  examples
>  src/scene_generation
 .gitignore
 LICENSE
 README.md
 pyproject.toml
 requirements.txt

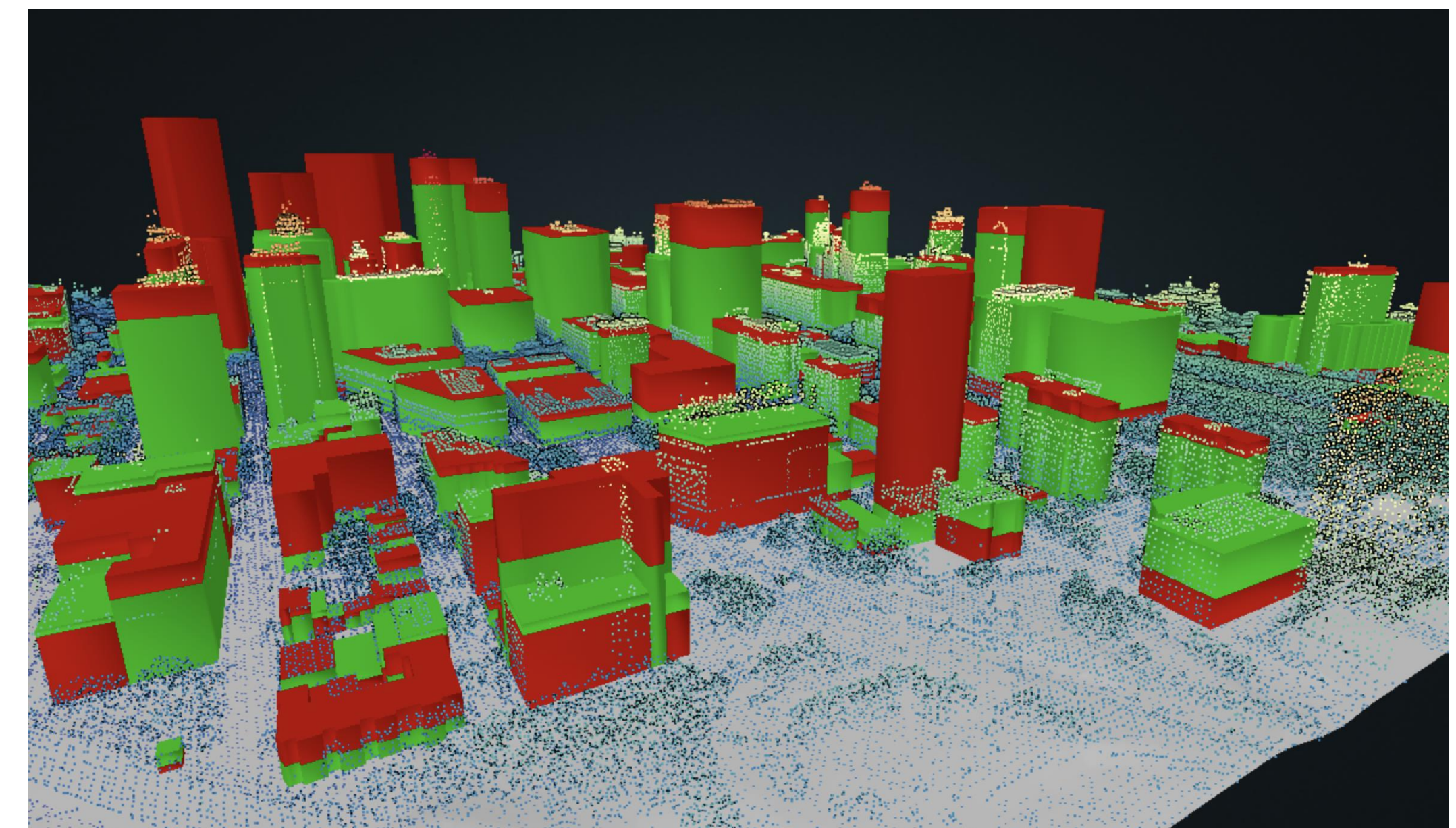
Name	Last commit message
 ..	
 antenna_Pattern	Adding the Sionna MSI Importer related file.
 1_sionna_coverage_map.ipynb	reorg t1-t5
 2_sionna_rays_analysis.ipynb	reorg t1-t5
 3_visualize_measurements.ipynb	reorg t1-t5
 4_ml_coverage_map.ipynb	Adding Sionna RT generated sparse measurements.
 5_scene_nist_28ghz_boulder.ipynb	reorg t1-t5

Geo2SigMap

- **v2.0 (Fall 2025)**
 - Support of lidar datasets
 - Support of irregular terrains
 - Tunable scene fidelity
 - Customized radio materials
 - ...



USGS lidar data availability map



Visualizing the lidar-based building height calibration process

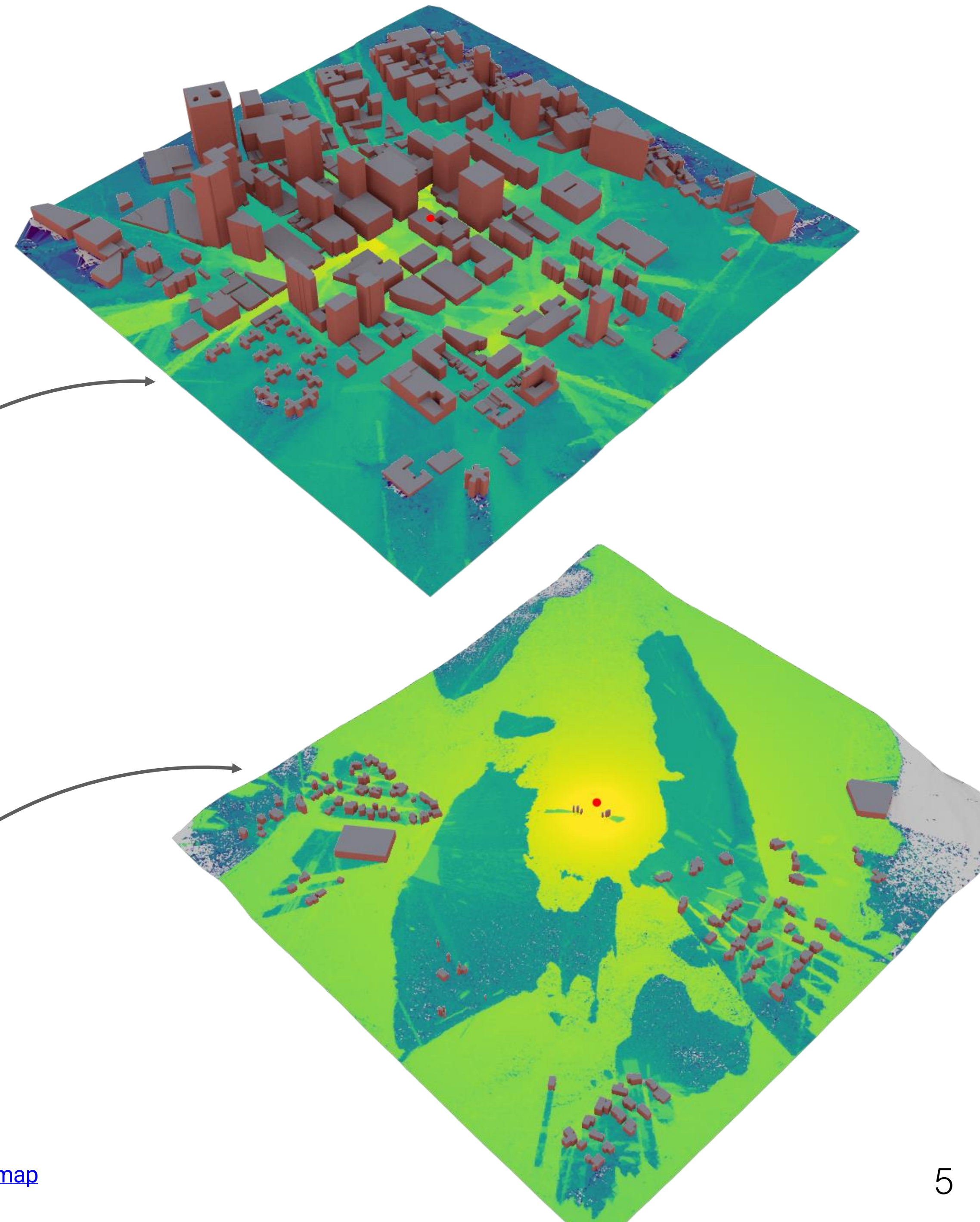
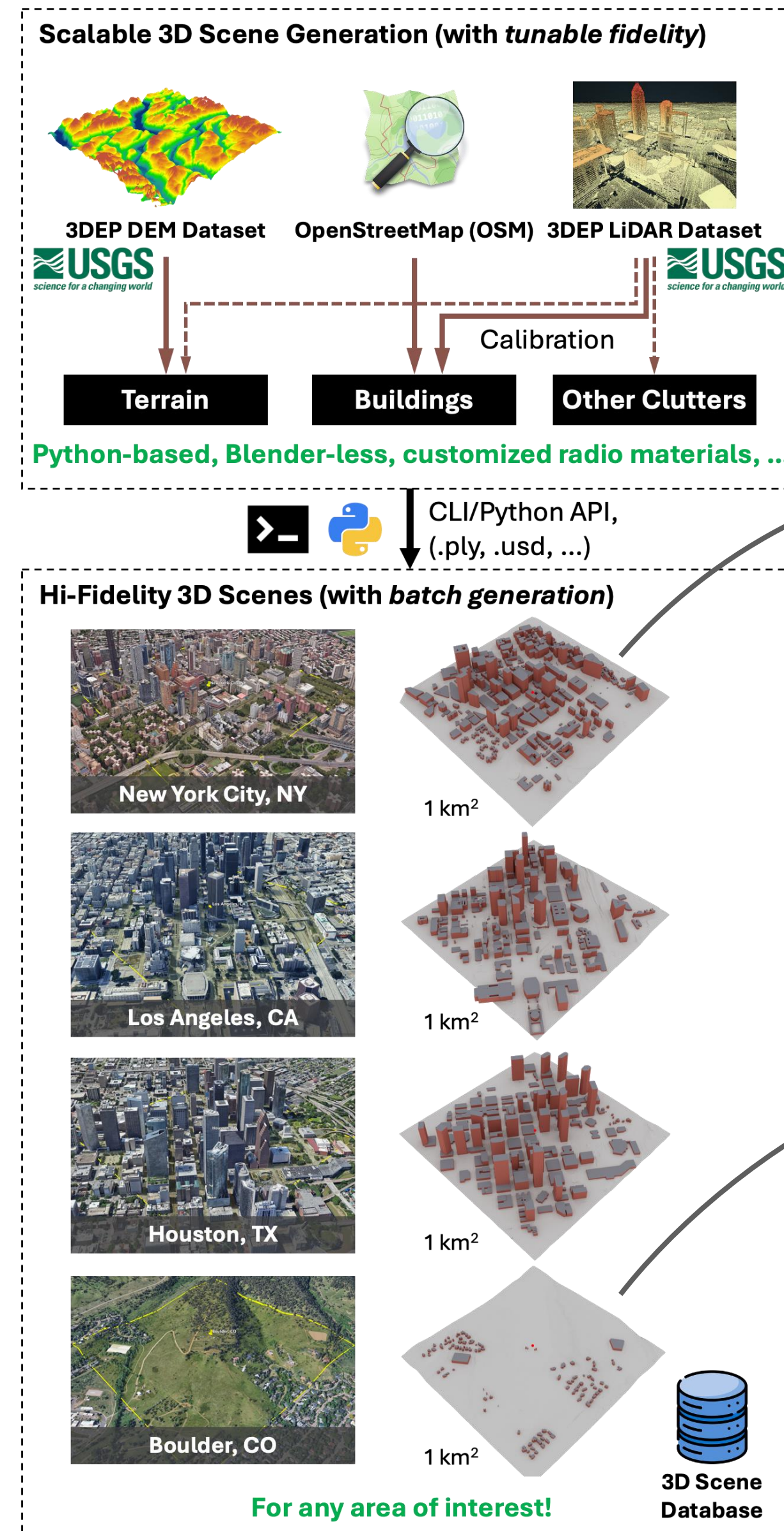
Geo2SigMap

- **v2.0 (*Fall 2025*)**

- Support of lidar datasets
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- ...

- **Input:** GPS coordinates of the target area and scene fidelity parameters

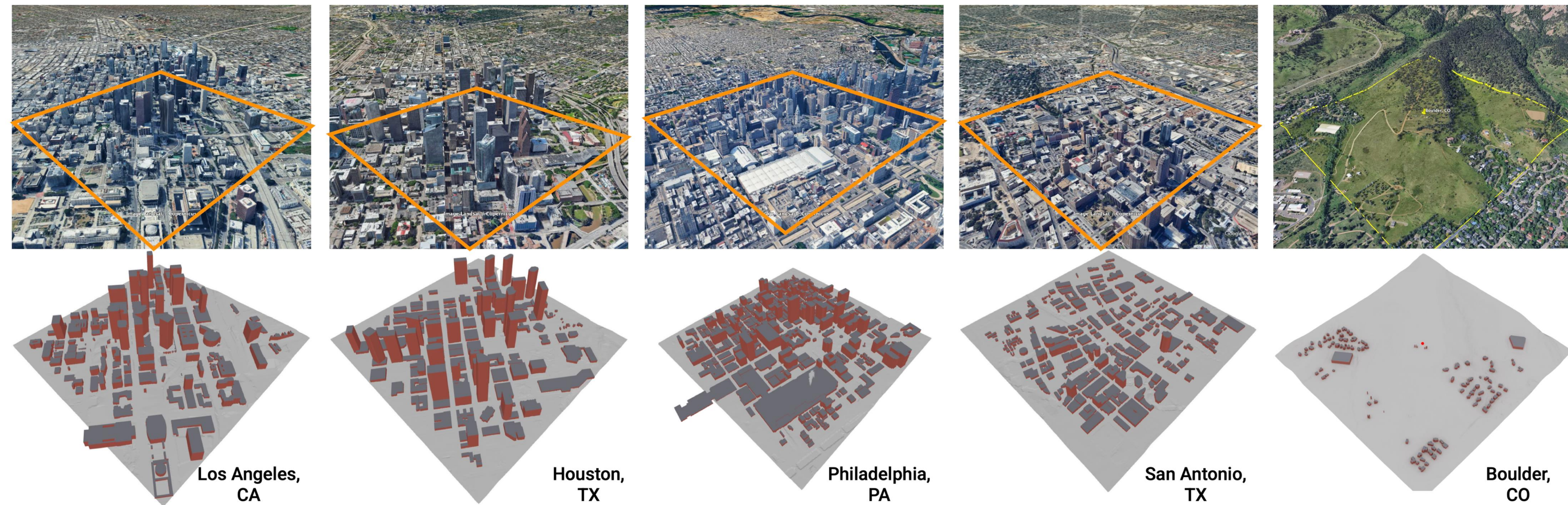
- **Output:** Sionna RT or AODT compatible 3D scenes



Geo2SigMap

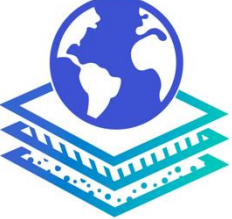
- **v2.0 (*Fall 2025*)**

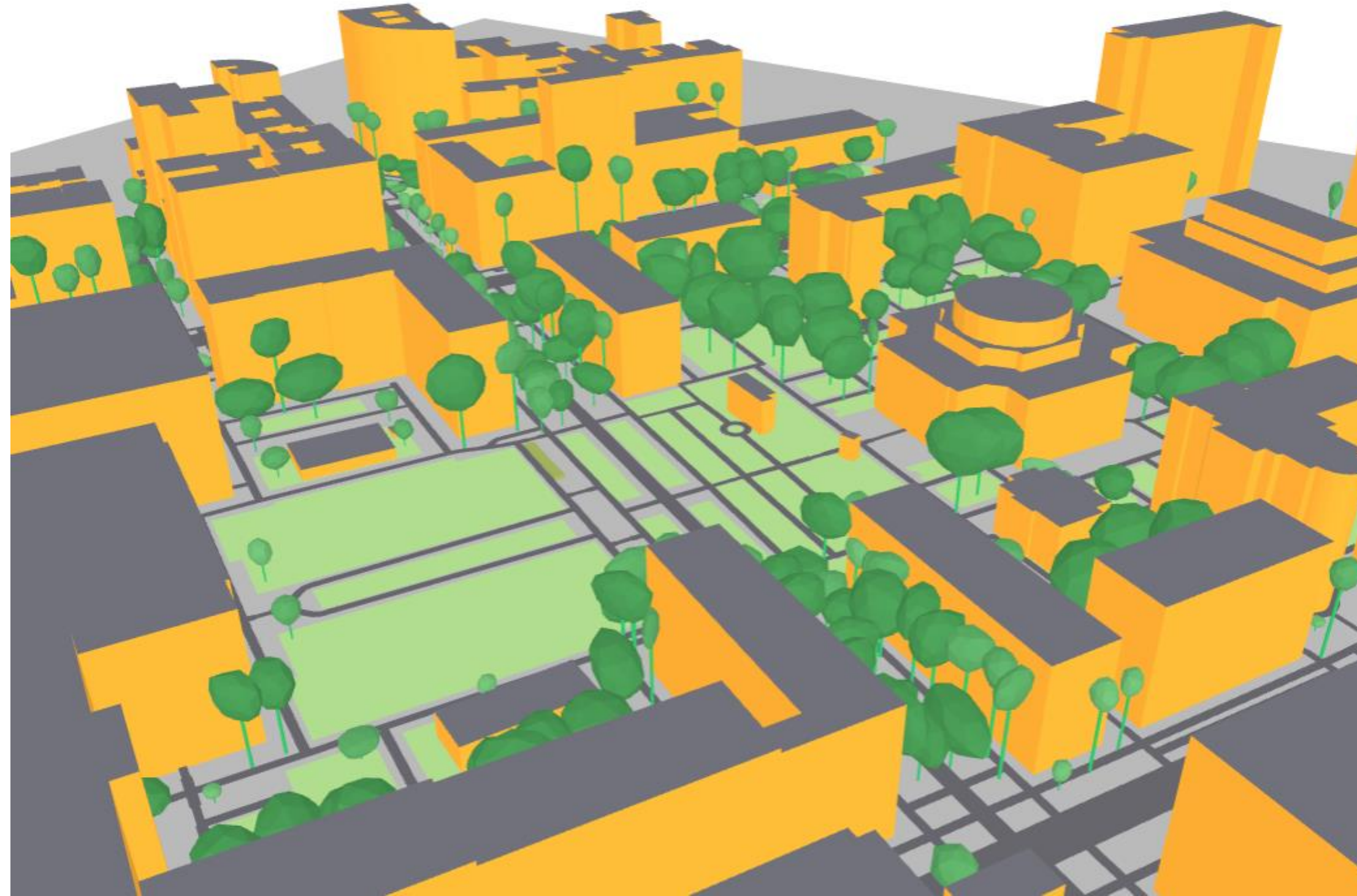
- Highly optimized batched 3D scene generation across 10s of 1000s of areas → Allow efficient generation of large scene datasets (and their ray tracing results and/or radio maps) for ML tasks



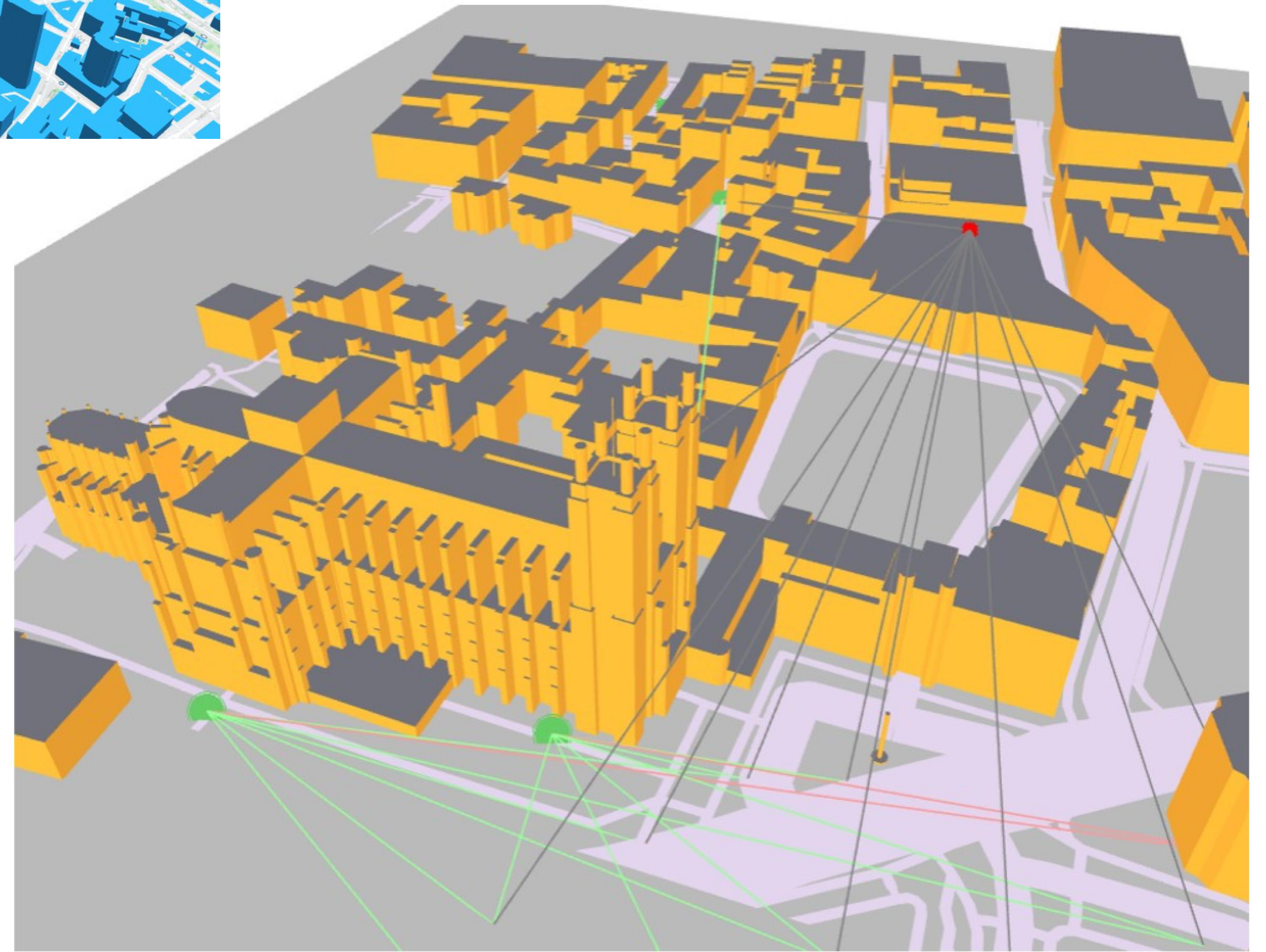
Geo2SigMap

- v2.1 (coming soon!)

- Support of  OVERTURE MAPS FOUNDATION



Columbia University campus with foliage



Sionna RT on Overture Maps based 3D scenes in Westminster, London

Geo2SigMap's Model Training and Evaluation

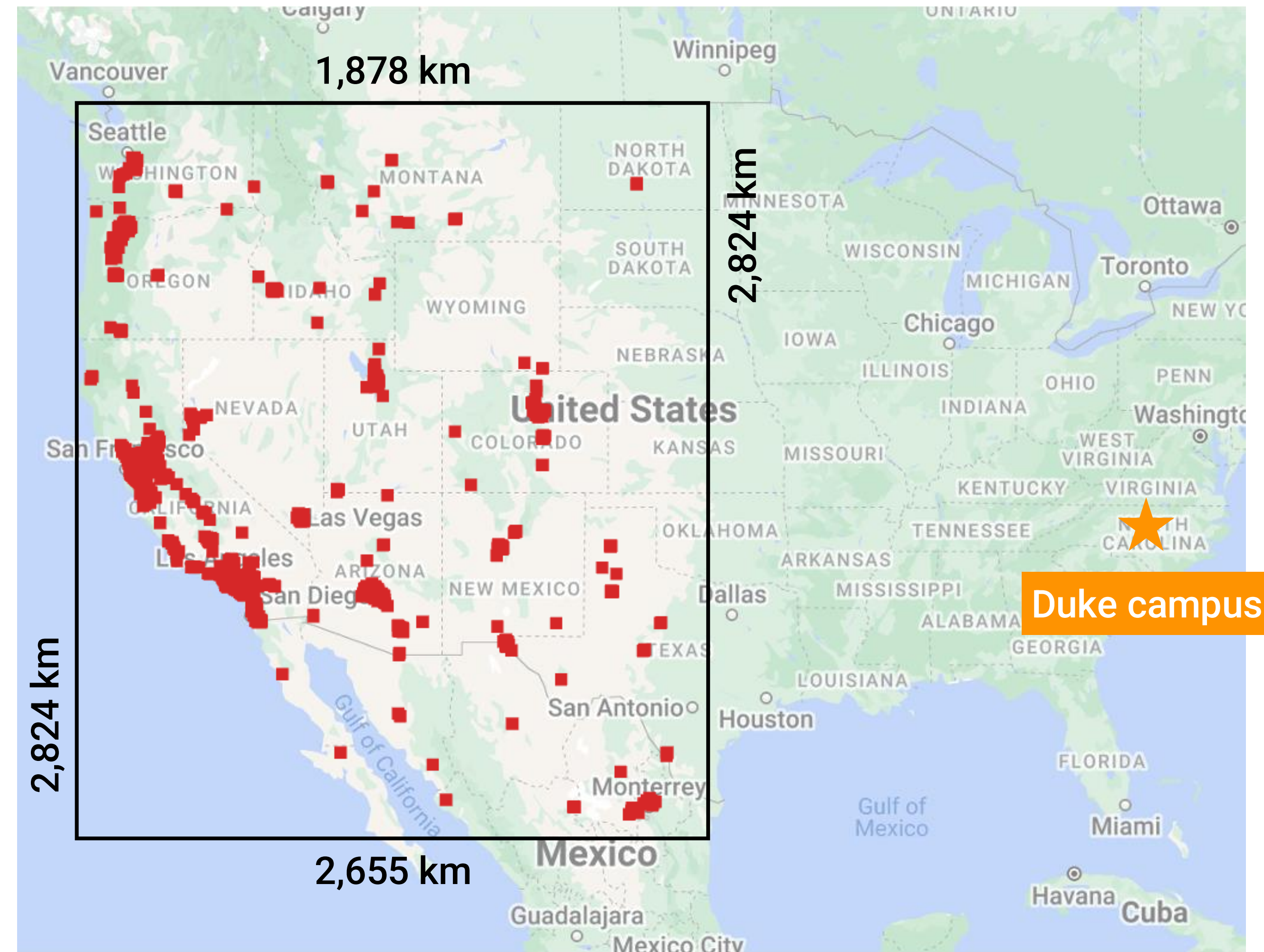
- No overlapped areas between the **training set** (RT simulation) and **testing set** (measurements)!

- **Model training**

- Dataset: ~27K areas, ~140K PG maps
- Loss function: MSE between the ground truth and predicted PG maps
- Training/validation split ratio of 0.8/0.2
- Model size: ~31M params.

- **Model evaluation**

- Dataset: ~57K CBRS measurements collected over 6 months on the Duke campuses
- With only 100 sparse measurements, the model achieves **an RMSE of 7.1 dB for predicting RF signal coverage for unseen areas**, outperforming existing methods by at least 4.0 dB



Thank you!
Questions?



tingjun.chen@duke.edu
<https://tingjunchen.com>



Semiconductor
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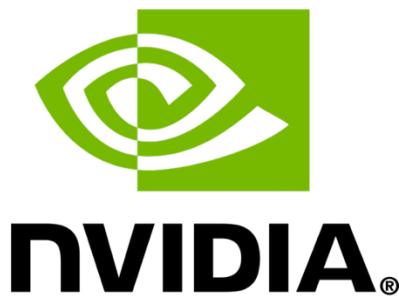
Platforms for Advanced
Wireless Research



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CUBiC

Center for Ubiquitous Connectivity