Validation by measurement and exposure on walks through ten cities

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2 Full-wave reference | 3 Indoor hybrid method | 4 Outdoor hybrid method | 5 Closed-form dosimetry | 6 Measurements and cities

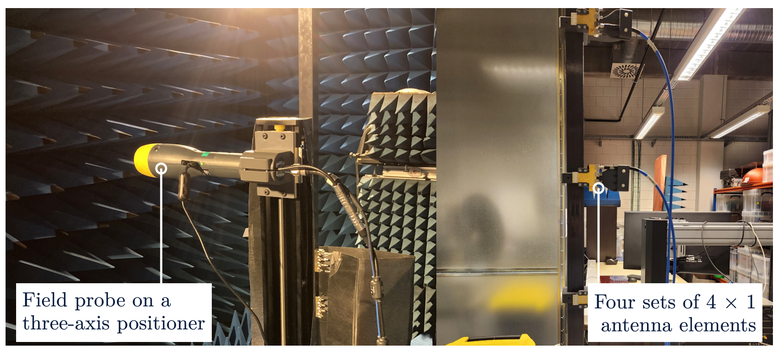
Along a line through a measured hot-spot, the field prediction has a 17% normalized mean absolute error. A digital twin of a stairwell predicts the interference pattern on a plane that was held out of its calibration. Across ten city routes, the highest median whole-body exposure is 14 times the lowest.

1 Question

Chapters 2 to 5 compare their methods with other simulations. How close are the measured and simulated fields? What is the exposure in a city where transmitter positions are unknown?

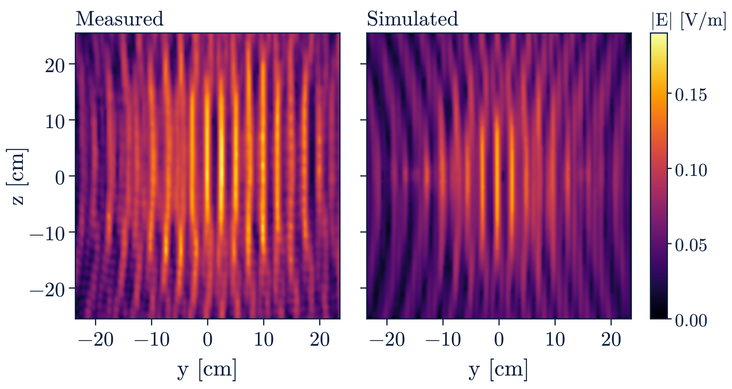
Scale	Frequency	Field from	Exposure from
Anechoic room	26 GHz	four antenna sets	none (field only)
Stairwell	28 GHz	ray tracing in a twin	law of Chapter 5
Ten cities	15 GHz	adjoint ray tracing	law of Chapter 5

2 Hot-spot in an anechoic room



Setup at 26 GHz. Phase shifters set the phase of four groups of four elements, so that all 16 add in phase at a point 62 cm away.

The probe scans 50 cm by 50 cm in steps of 3.33 mm, which takes 50 hours. The simulation sums four spherical waves, one per set, with the simulated set patterns and measured amplitudes, as in Chapter 4.



Electric field in the scan plane. Both maps have the wide region of the four beams, the fringes and the peak at the center.

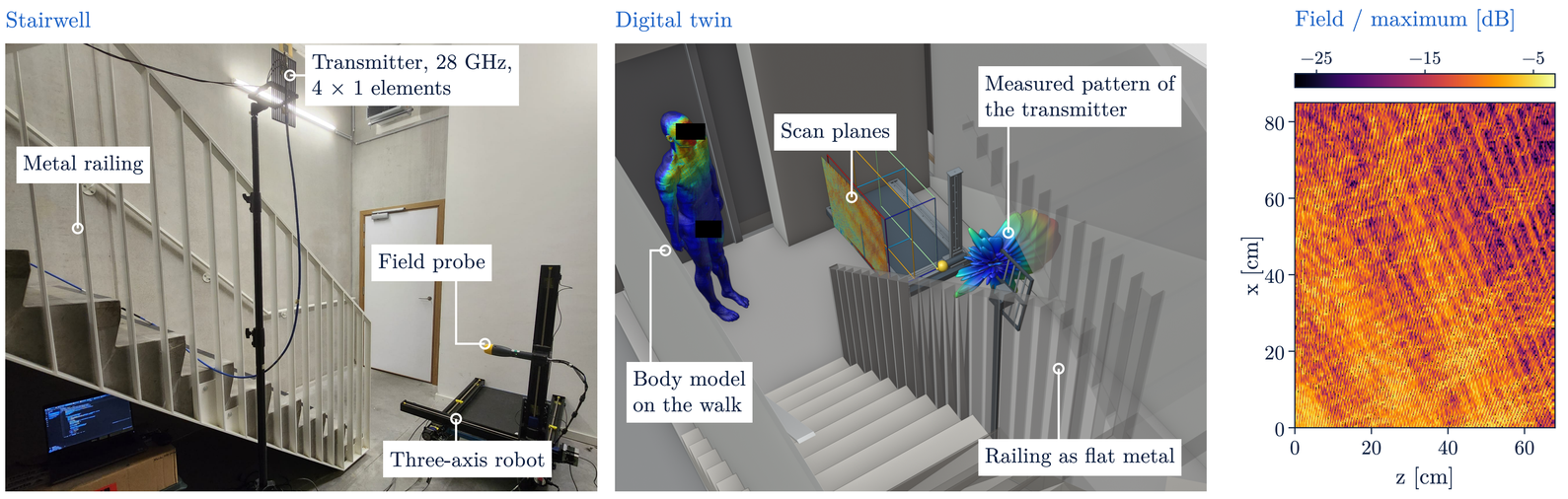
	Measured	Simulated
Peak field	0.19 V/m	0.17 V/m
Width of the central peak	0.93 cm	0.94 cm
Normalized mean absolute error	17% ± 10% (0.65 dB)	

Values are along the horizontal line through the center. The higher measured field on the right is attributed to scattering by the 48.5 cm probe, omitted from the simulation.

54 dB
below the basic restriction for the milliwatt source in the stairwell, least favorable calibration

314 s
ray and body calculation for 163 points in ten cities, on one A6000 GPU

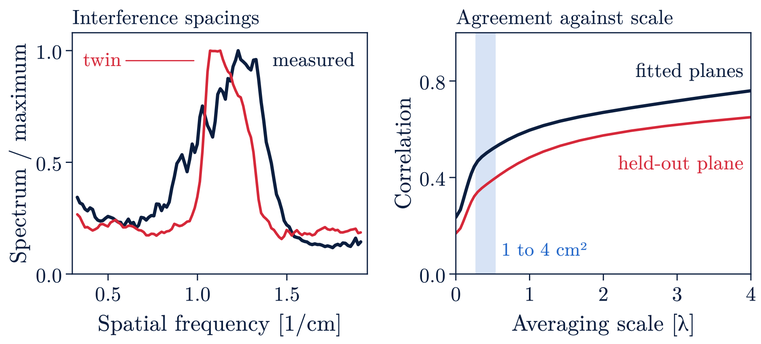
3 Stairwell and digital twin at 28 GHz



Left: a robot moves the probe over five planes in 31 hours. **Center:** the twin is built from the architectural model of the building. Ten pose and eight material parameters are calibrated. **Right:** the plane that was held out of the calibration.

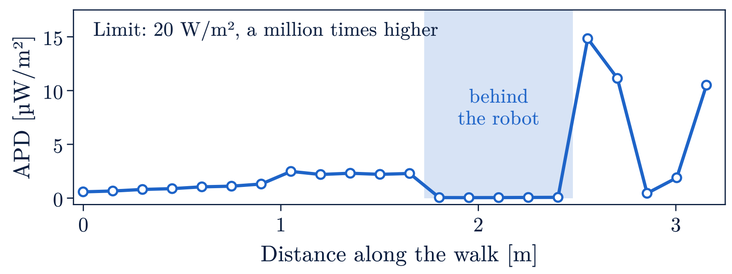
4 Prediction of a held-out plane

The probe measures only the field magnitude. We calibrate the twin on three planes and test it on the fourth, holding out each plane in turn.



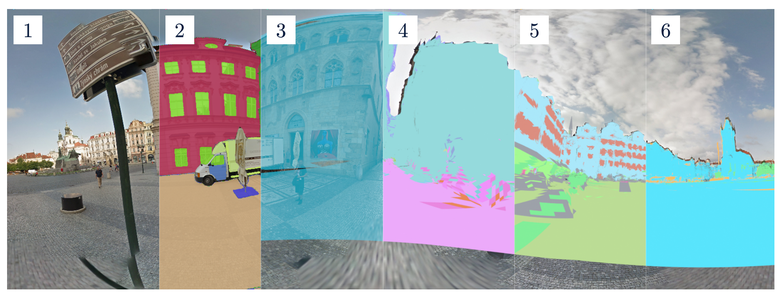
Held-out plane. Left: spectrum of the field along the scan lines. Right: correlation after averaging over a Gaussian window. Band: averaging areas of the ICNIRP guidelines.

Across four held-out planes, beat-spectrum correlation is 0.55 to 0.79. On this plane, pointwise correlation is 0.17 before averaging and 0.65 after averaging. The largest error is due to the railing's grating response.



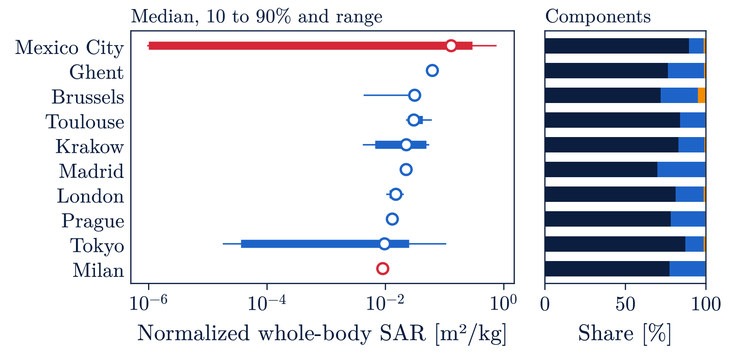
Absorbed power density over 4 cm² on a walk toward the transmitter, which radiates milliwatts. The Chapter 5 law uses the twin's field on a Huygens box. Calculation time is 31 s for 22 positions.

5 Ten cities at 15 GHz



Prague, Old Town Square. 1 street image, 2 object labels, 3 city mesh, 4 combined objects, 5 material labels, 6 input of the ray tracer.

Materials on visible mesh faces are assigned from street images. Unseen faces have a default material. Hypothetical sources are uniform along visible rooflines. The cost of receiver-to-source ray tracing is independent of source count.



Whole-body specific absorption rate (SAR) on ten routes, per unit of transmitter density and power. Right: direct (dark), specular (blue) and diffuse (amber) shares.

Direct paths are the largest component at 156 of 157 line-of-sight points. Six shadowed points receive only diffuse power. The factor of 14 depends on source placement, geometry and materials.

6 Conclusions

- The normalized mean absolute error of the hybrid method is 17% along a line through the measured hot-spot.
- A twin calibrated on magnitudes predicts averaged fields better than point values, and the limits apply to averages.
- The calculation time for ten cities is about five minutes. Outdoor measurement validation is future work.
- The models omit the probe, the robot and the grating response of the railing. Each case uses a single frequency and body model.

References

[1] R. Wydaeghe *et al.*, "New hybrid ray-tracing/FDTD for EMF exposure in 6G networks using semantically classified Google Earth photogrammetry with measurement validation," in *Proc. EuCAP*, Glasgow, 2024. [2] R. Wydaeghe *et al.*, "Holographic phase retrieval of RF-EMFs for human exposure assessment using fine 3D electric field measurements in a real environment from a beamforming 28 GHz antenna," in *Proc. EuCAP*, Stockholm, 2025. [3] R. Wydaeghe *et al.*, "Digital twin calibrated from phaseless 28 GHz measurement scans for indoor exposure assessment," manuscript submitted to *IEEE Antennas Wireless Propag. Lett.* [4] R. Wydaeghe *et al.*, "Human-centric 6G RF-EMF exposure with AI-assisted digital twins in ten cities," manuscript submitted to *IEEE Open J. Commun. Soc.*

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