

An overall vision of electromagnetic propagation in built-up areas

Giorgio Franceschetti
Università Federico II of Napoli, Italy
and
UCLA, USA

Preliminary Considerations

Why electromagnetic propagation?

The capacity of a wireless network depends on the physics of propagation. We need to develop analytical models of propagation to compute the fundamental limits of wireless communication.

Maxwell Equations

in complex environments



$$\nabla \times \vec{E} = - \frac{\partial \vec{B}}{\partial t}$$

$$\nabla \cdot \vec{D} = \rho$$

$$\nabla \times \vec{H} = \frac{\partial \vec{D}}{\partial t} + \vec{J}$$

$$\nabla \cdot \vec{B} = 0$$

- No closed form solution
- Use approximated numerical solvers

Alternative approach

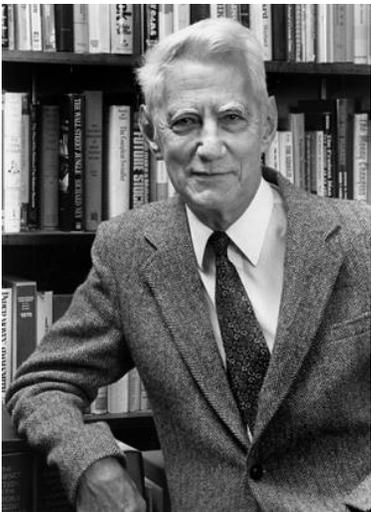
Stochastic characterization of the environment

Few parameters

Simple analytical solutions

*The true logic of this world
is in the calculus of probabilities.*

James Clerk Maxwell



Using these stochastic models,
Shannon's entropy is useful
to understand the nature
of propagation

Is this business over?

New **ideas**

and

new **approaches**

must be explored and developed

to comply with the

new **emerging technologies**

Table of Content

- The city ensemble
- The deterministic approach
- The probabilistic approach
- The next step

The city ensemble

- The cities' distribution may be considered as a stochastic process, each city being an element of this ensemble
- The electromagnetic propagation in the city becomes the problem of searching the solution of Maxwell equations in a stochastic environment
- This task may be pursued on along essentially *two lines of thought*: either a *deterministic* or a *stochastic* one

The Deterministic Geometrical Model (DGM)

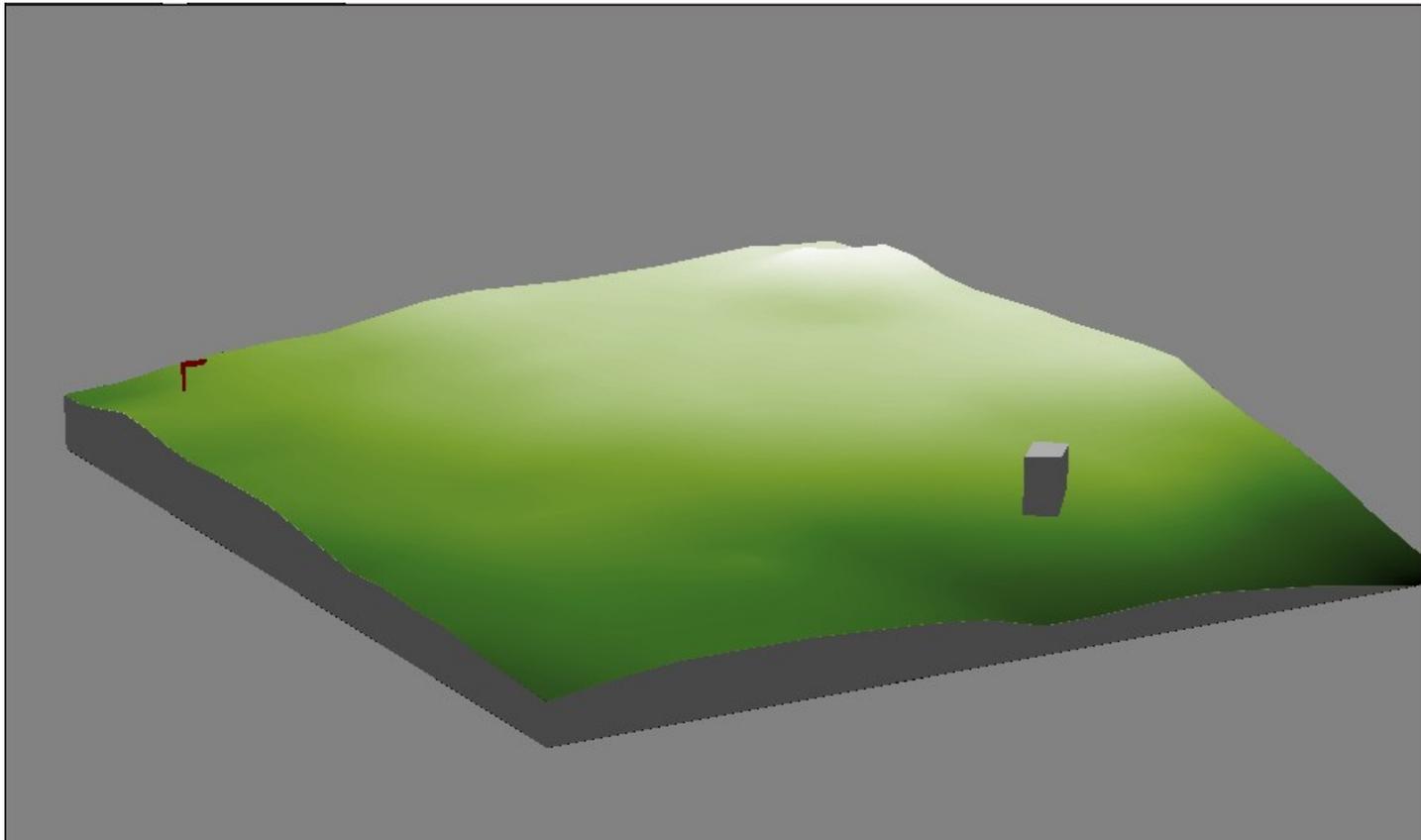
- An element of the cities' ensemble is chosen, namely the particular city of interest
- Knowledge of the three-dimensional geometry of the city must be known, i.e., shape and location of each building
- Buildings are schematised in terms of parallelepipedic structures
- *Ray tracing procedures* are implemented to compute the electromagnetic field everywhere outside, i.e., in the streets and squares of the city, and perhaps also inside the building

Implementation Procedure

- Environment geometry
- Buildings schematisation
- Transmitting antenna files
- Electromagnetic and electromagnetic related parameters
- Mathematical algorithms

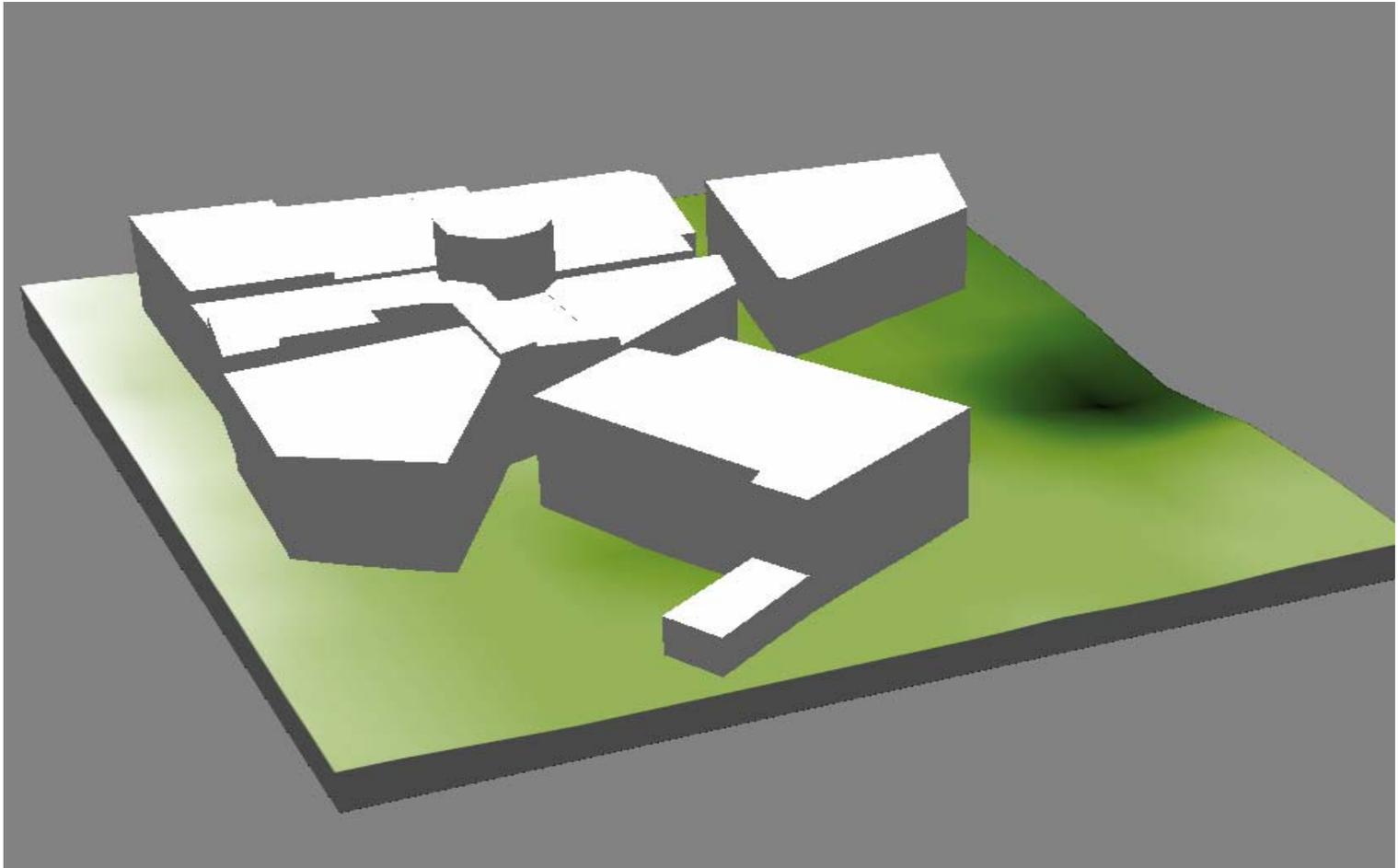
Environment geometry

File raster (Digital Terrain Model)



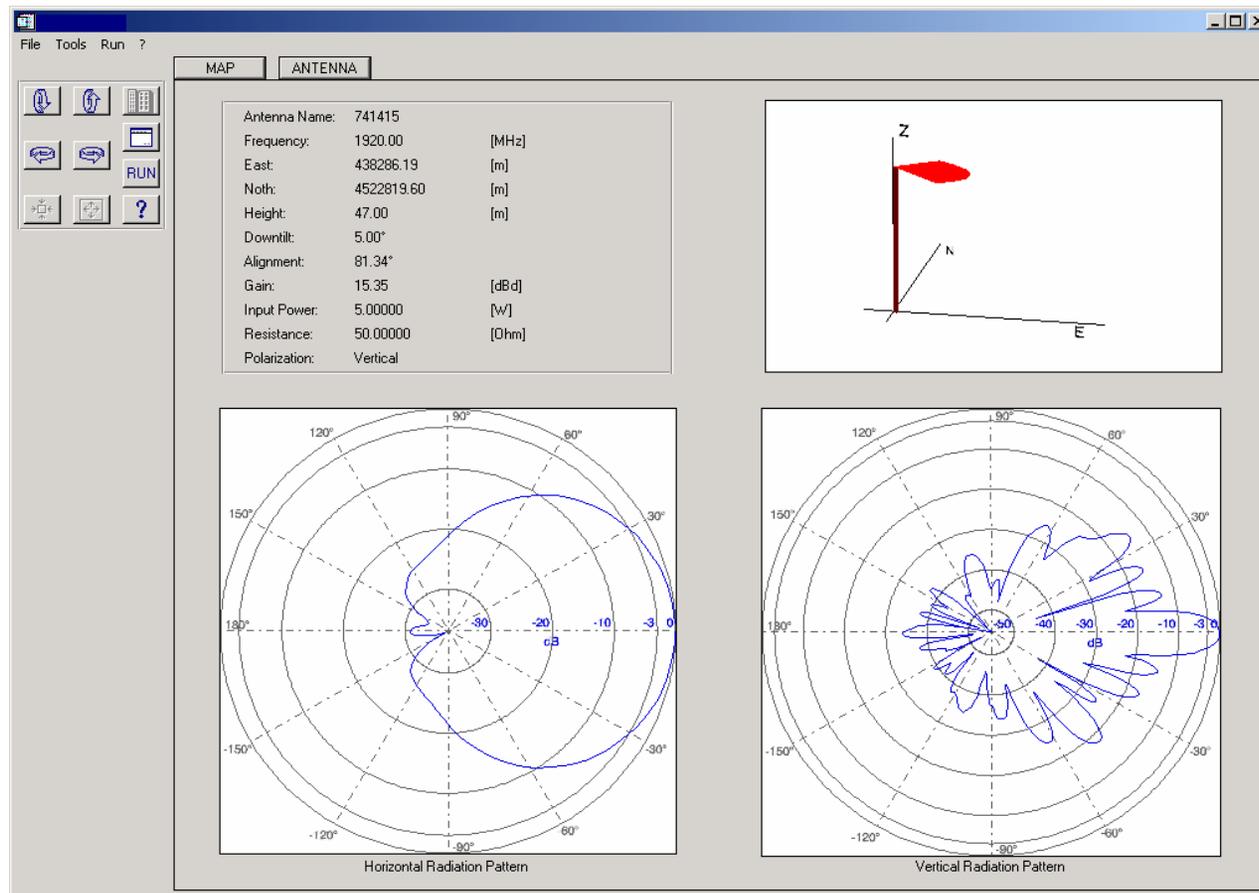
Buildings schematisation

Three-dimensional (3D) buildings representation



Transmitting antenna files

Radiation diagram in the two principal planes



Electromagnetic and electromagnetic related parameters

- Buildings' walls complex permittivity
- Walls' thickness
- Windows' area percentage
- Thickness of windows' glass
- Complex permittivity of windows' glass
- Indoor attenuation factor
-

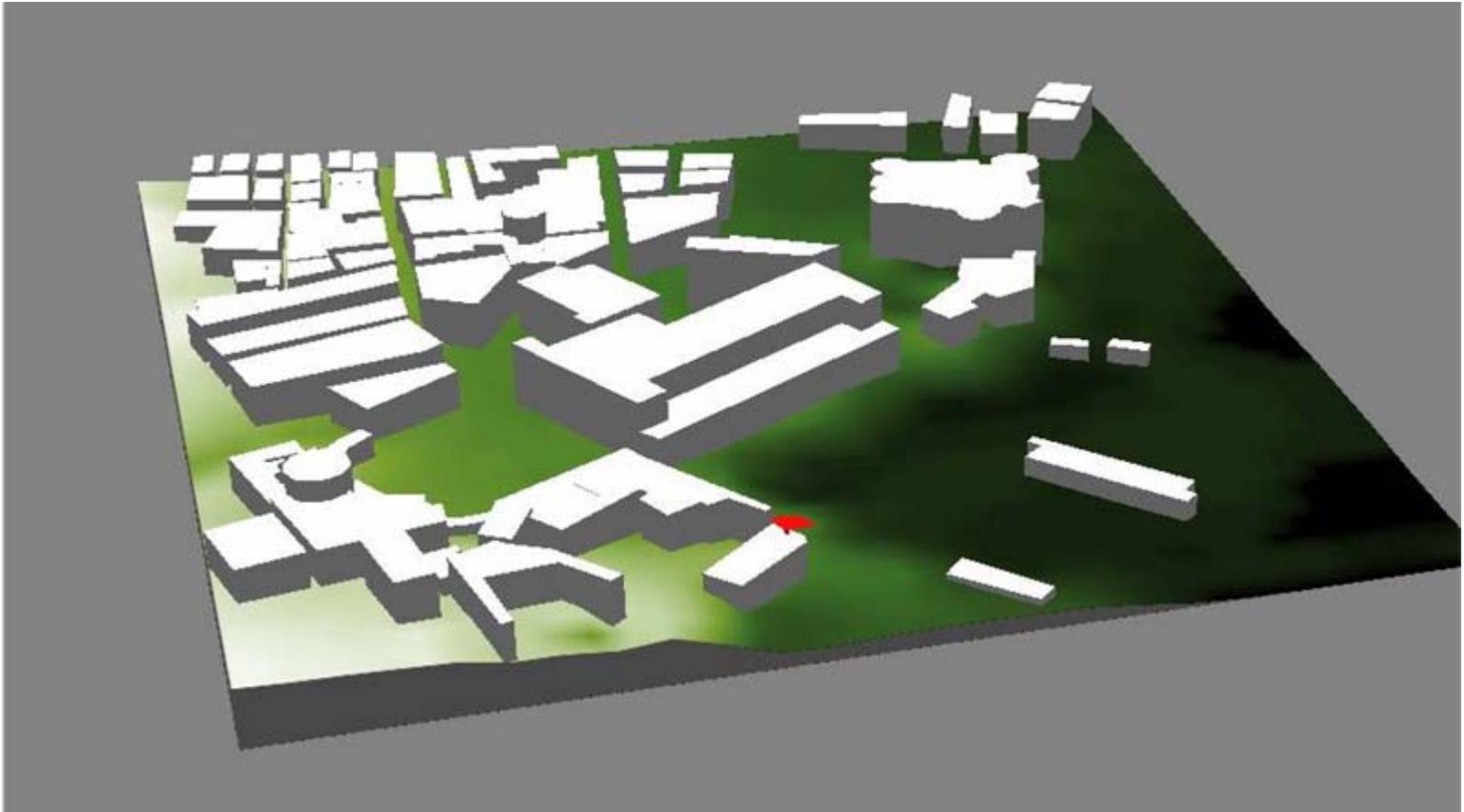
Mathematical algorithms

- Ray-tracing
- Geometrical Optics (interaction with finite dimension obstacles)
- Geometrical/Uniform Theory of Diffraction (GTD/UTD) for buildings' edges diffractions
- Creeping rays for roofs' propagation and diffraction
- Outdoor-Indoor Field

Example

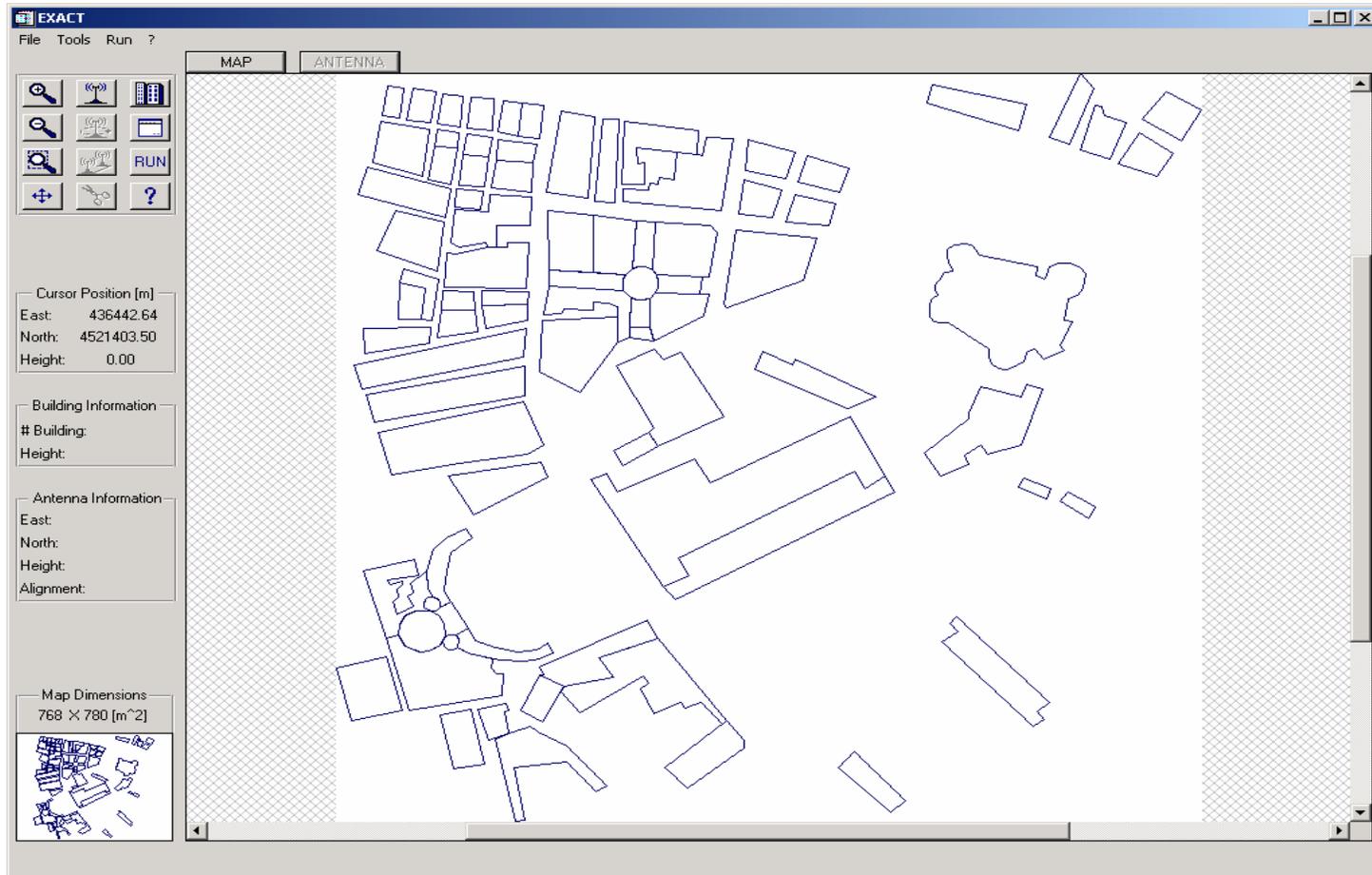
[Plebiscito Square, Napoli, Italy]

City geometry (3D)

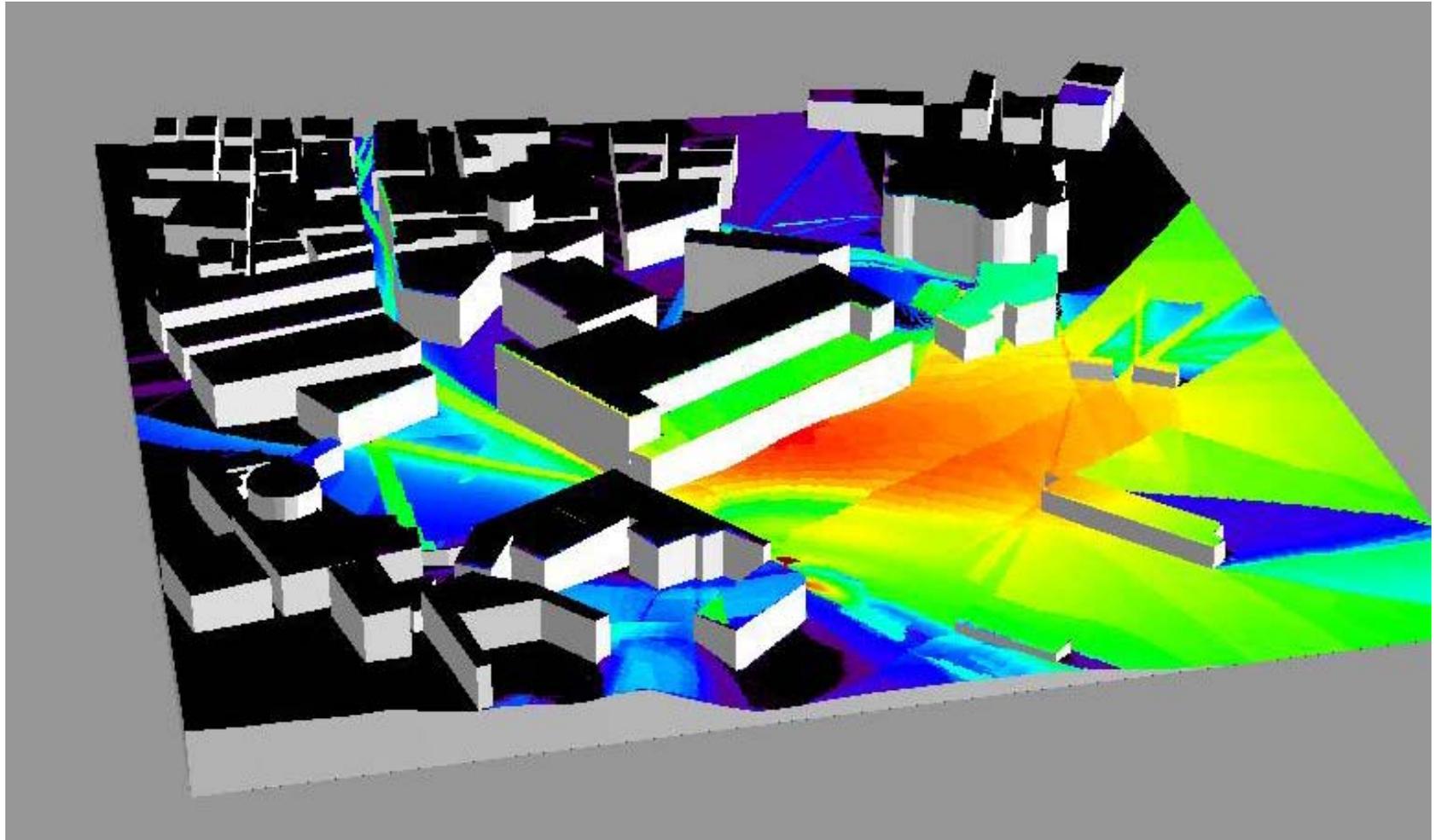


Example

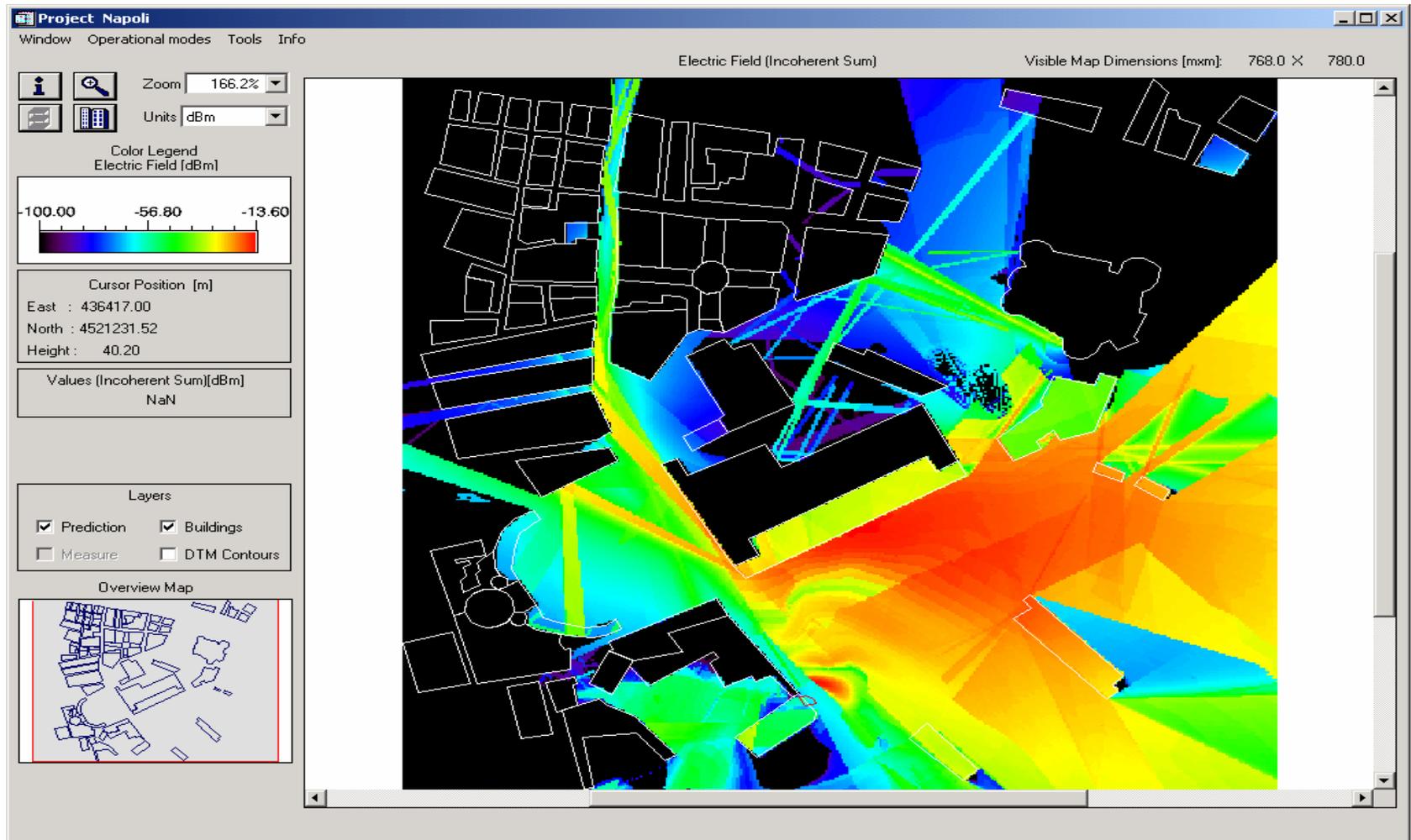
Corresponding 2-D plant



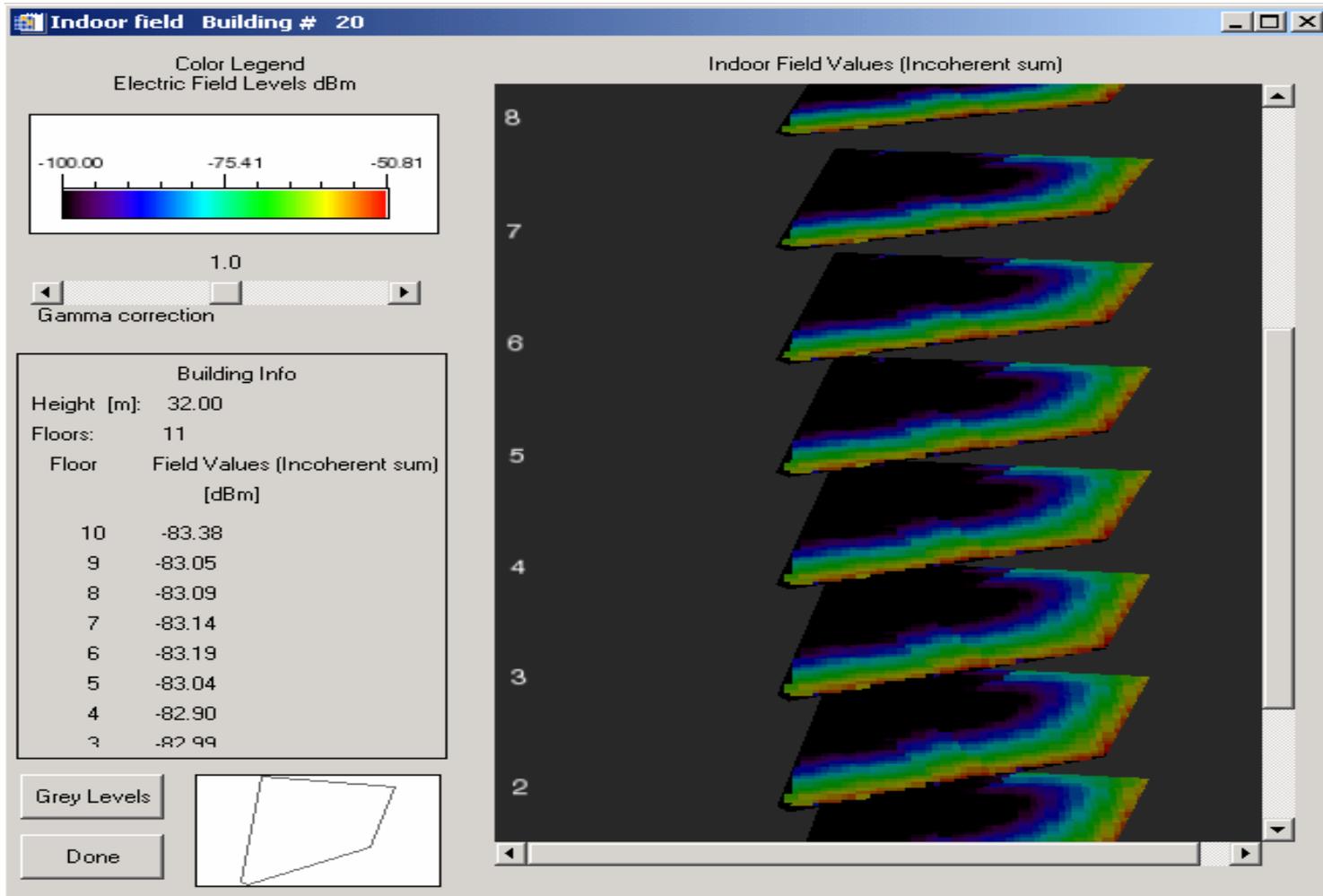
False color 3-D simulation of the radiated field



Corresponding 2-D representation of the radiated field



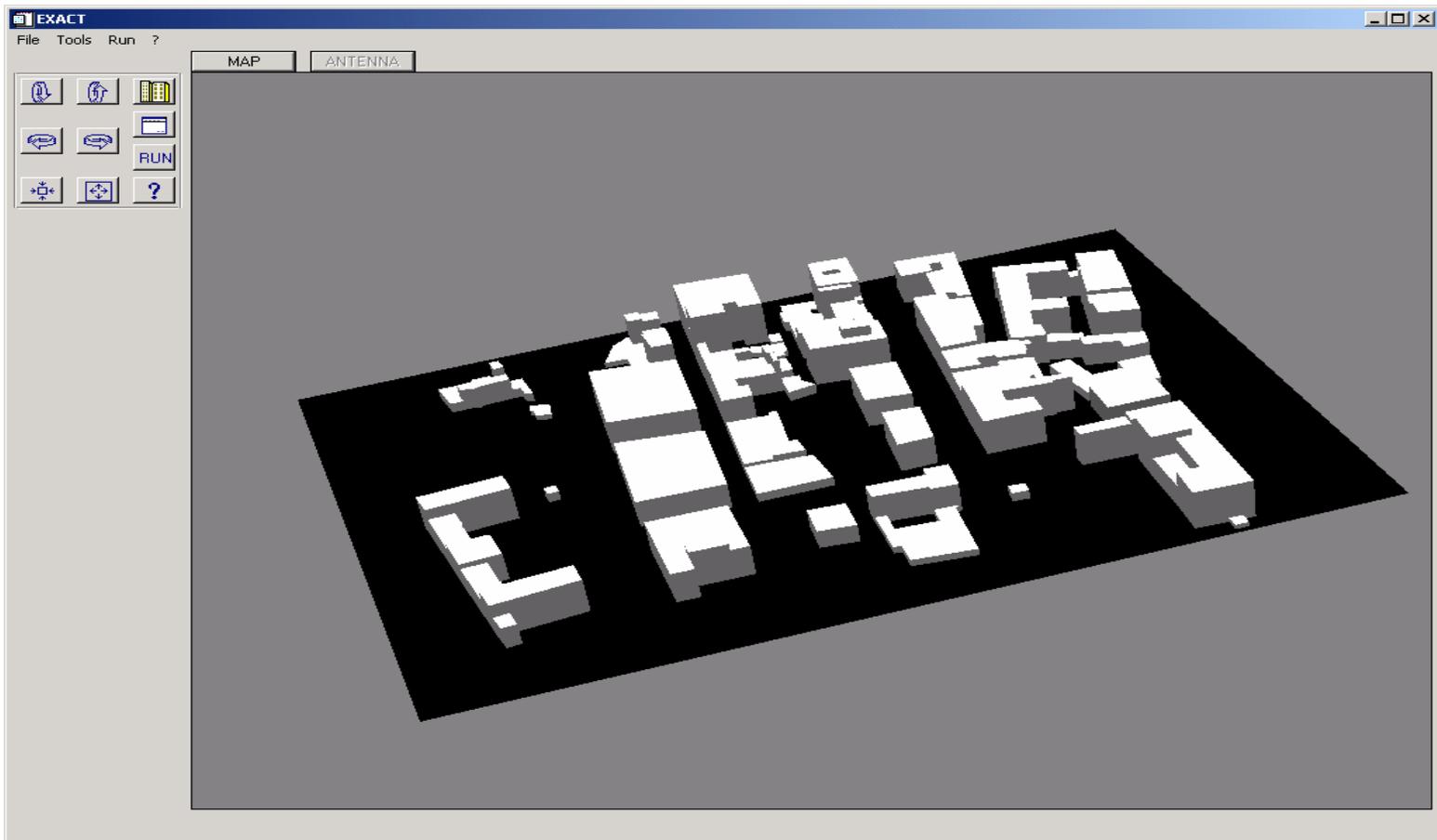
Outdoor-Indoor radio coverage



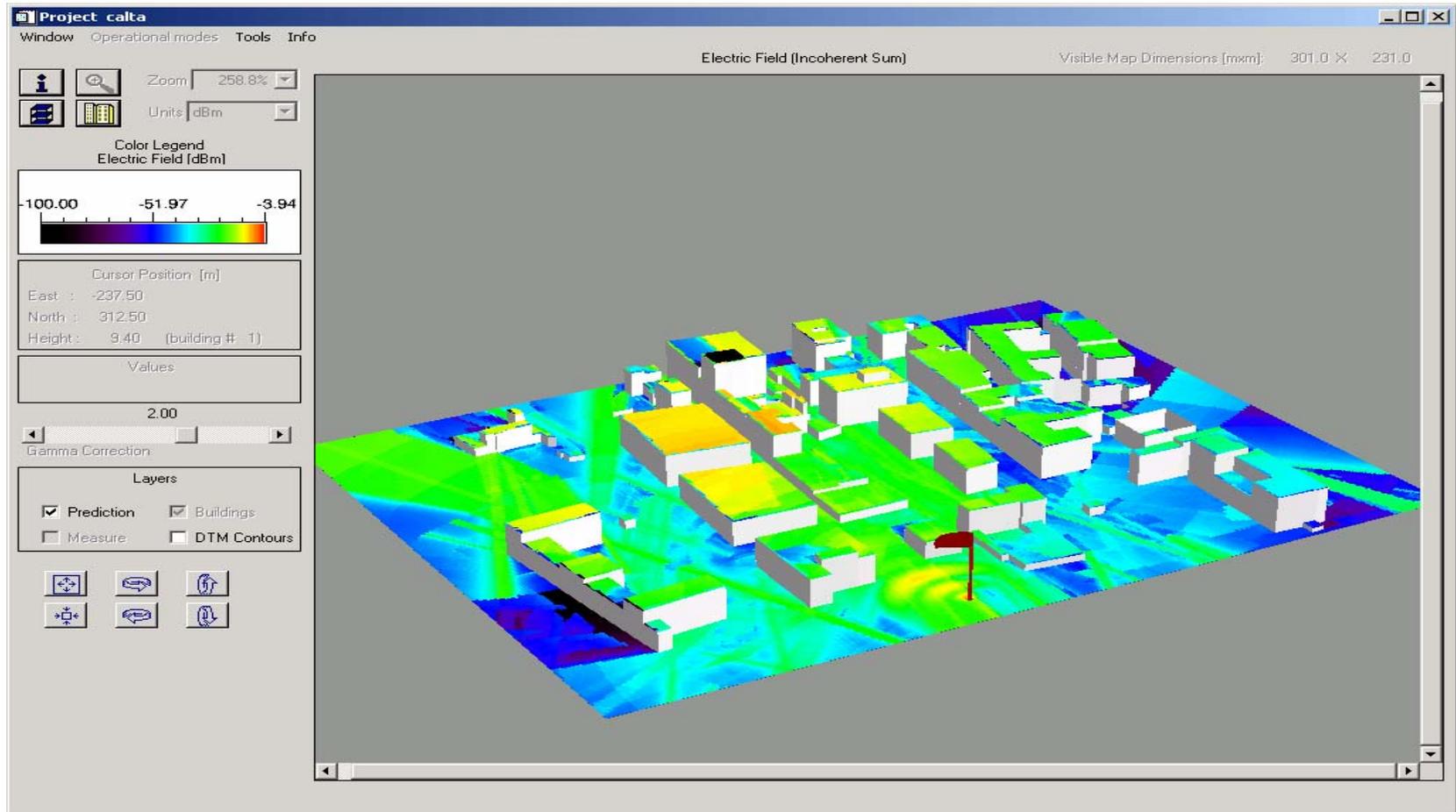
Additional example

[Roma Square, Caltanissetta, Sicily, Italy]

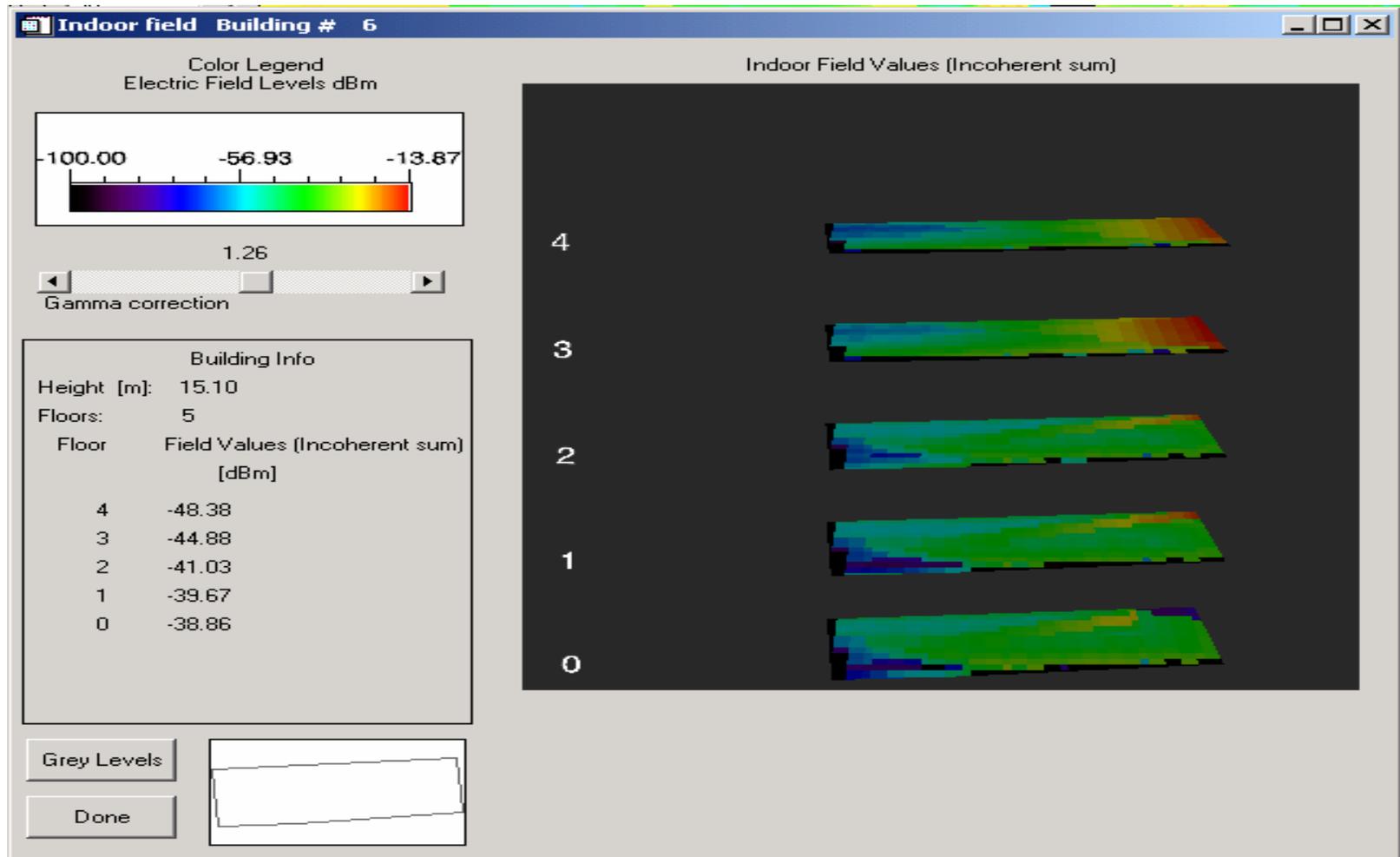
3-D geometry of the city



3-D simulation of the radiated field



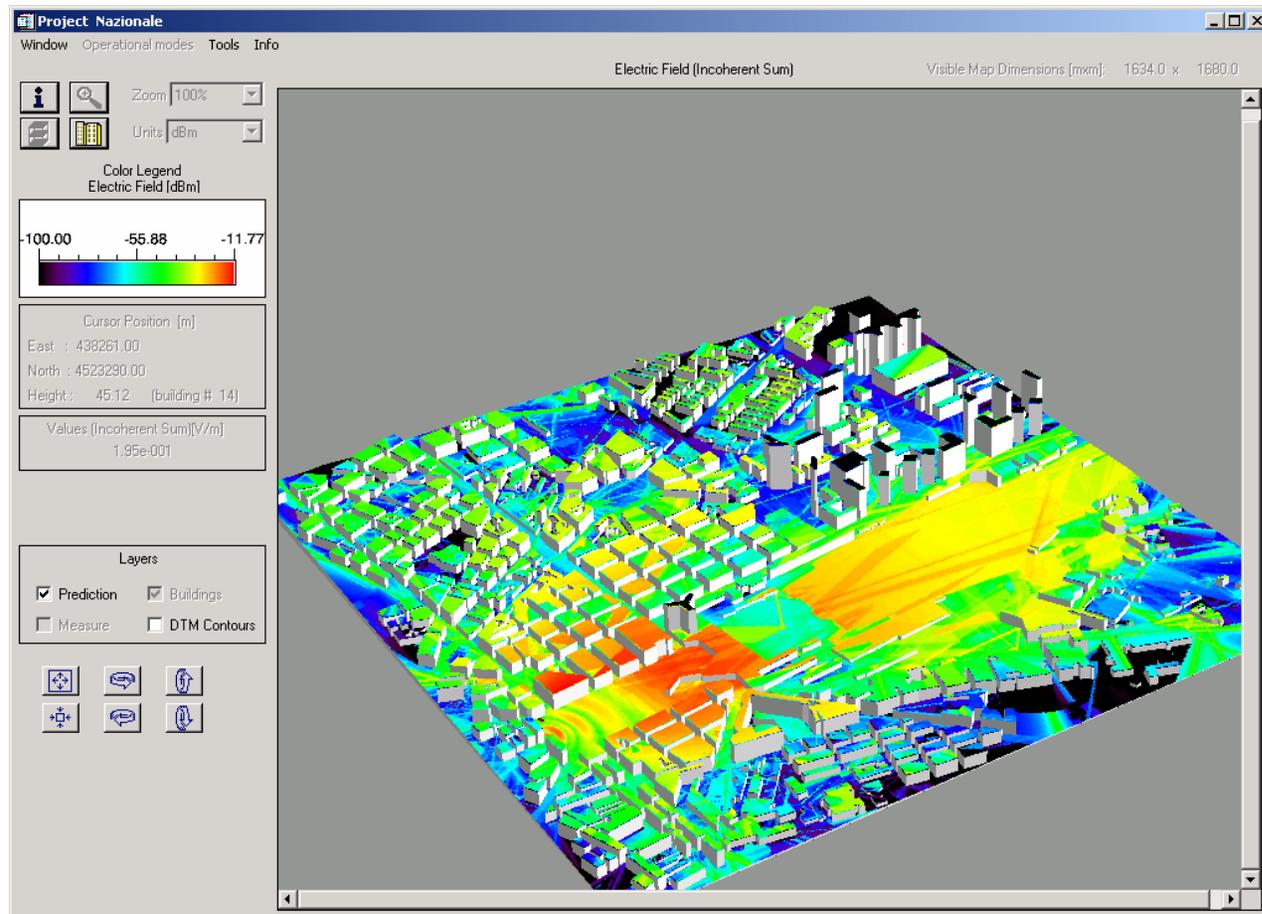
Outdoor-Indoor radio coverage



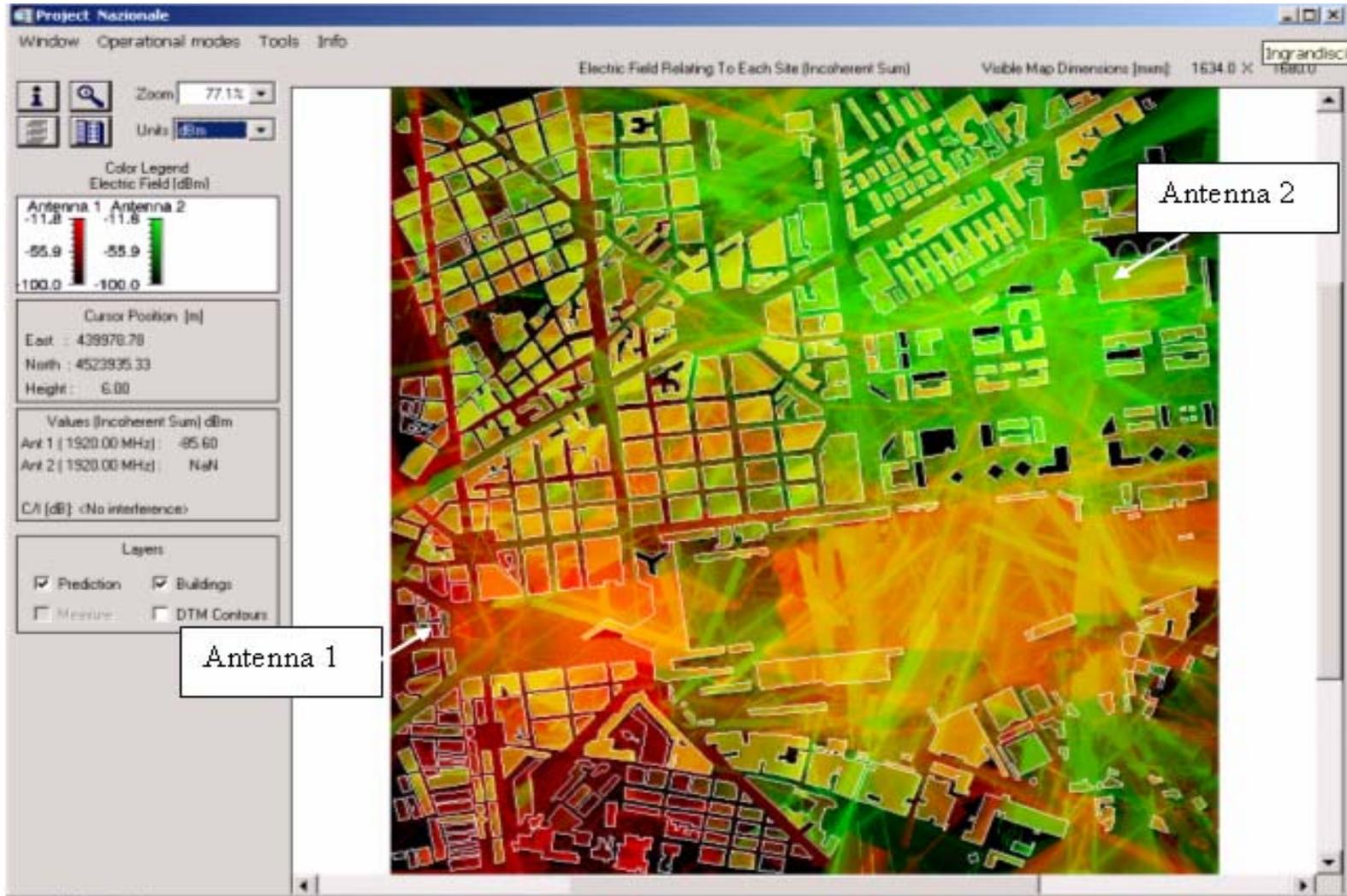
Additional example & applications

[Railway station section of Napoli, Italy]

3-D simulation of the radiated field



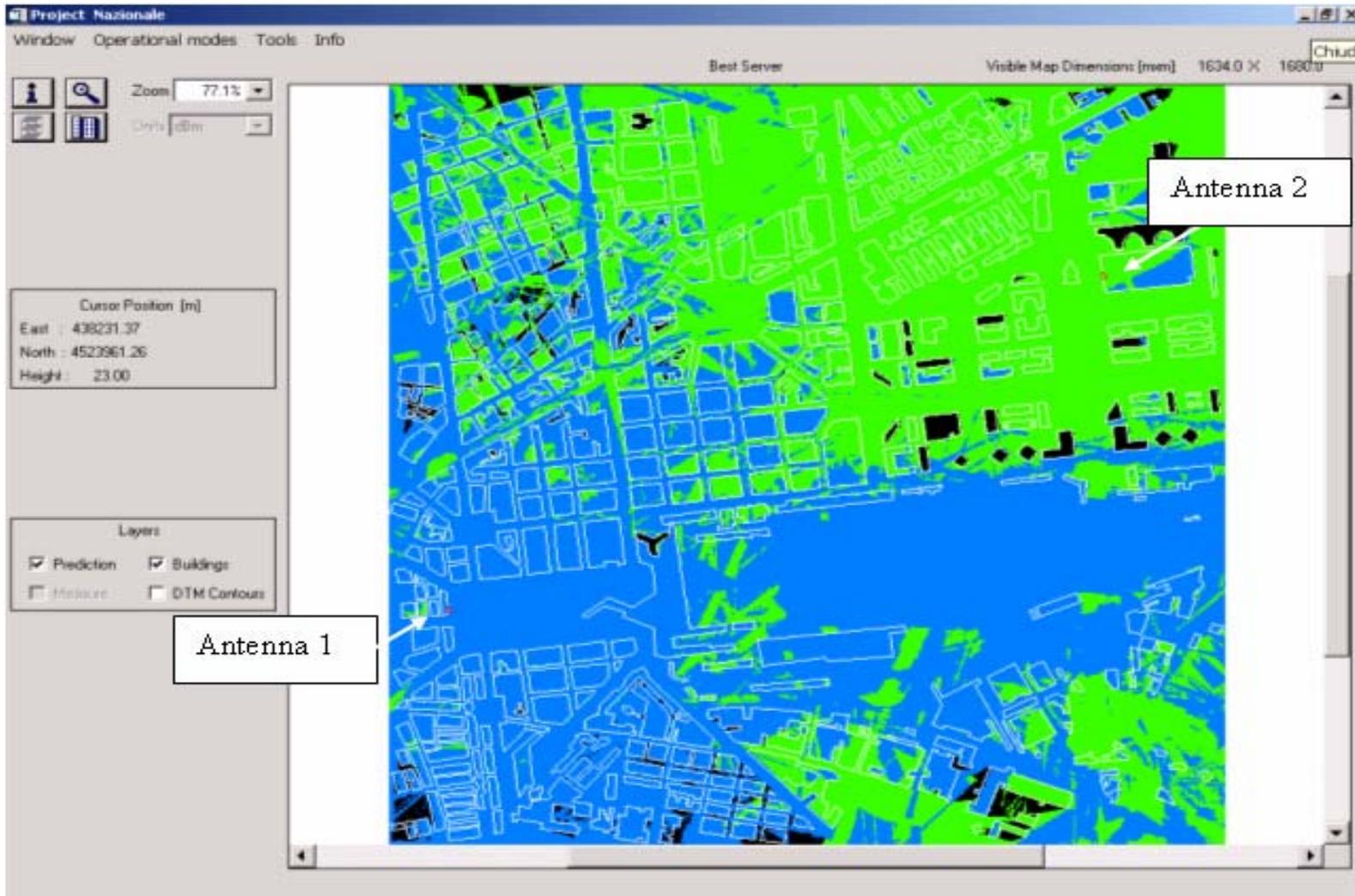
Co-Channel Interference



DGM cnd.

Add. Ex. & Appl. Cnd.

Best server

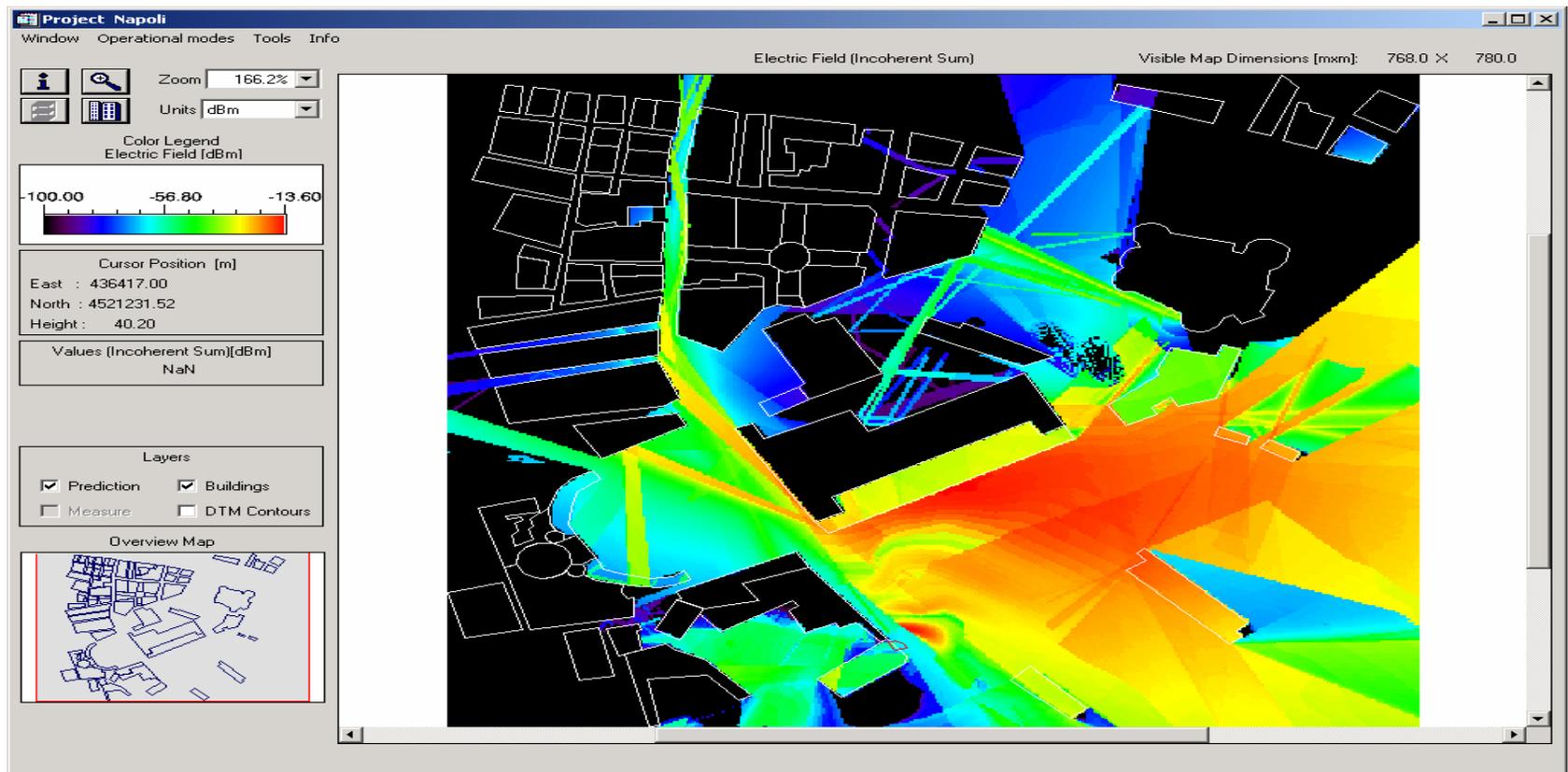


Deterministic Geometrical Model features

Attractive features

- Canyon effect well described
- Illumination in geometrically obscured areas is provided
- Modulated and/or transient signals can be accounted for

Canyon effect is well described &
illumination in geometrically obscured
areas is provided



Modulated and/or pulsed signals can be accounted for

- The field illumination $E(\omega, r)$ excited by a sinusoidal signal radiated by a unitary current is computed
- The frequency spectrum $F(\omega)$ of the antenna input current is computed

- For modulated signals, the illumination baseband field is given by

$$\hat{E}(\omega, r) = E(\omega, r) F(\omega) \exp(-i \Omega t),$$

Ω being the carrier angular frequency

- Then, the (inverse) Fourier Transform of $\hat{E}(\omega, r)$ provides the illumination modulating signal
- For pulsed signals, the illumination pulsed signal is given by the (inverse) Fourier Transform of $E(\omega, r) F(\omega)$

Limitations

- Model validity
- Adopted algorithm precision
- Computational efficiency

Model validity



Model validity cnd.

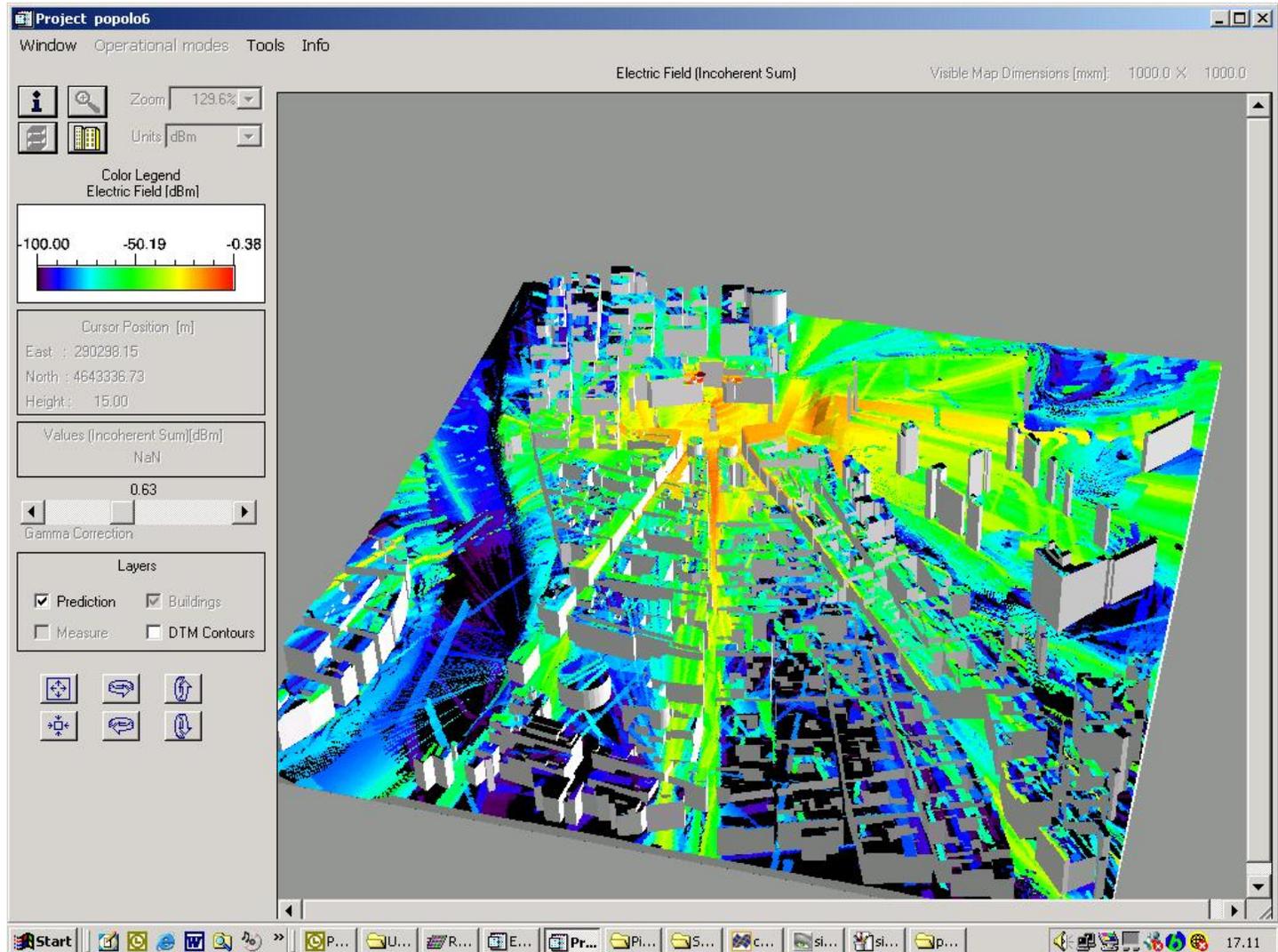


Adopted algorithm precision

- Reflected rays are computed under the assumption of smooth reflecting surfaces, usually of infinite extent
- Diffracted rays make use of heuristically modified diffraction coefficients, accounting for the dielectric nature of buildings' edges
- Transition function in the lit-shadow regions make use of simplified expression to speed up computations

Experimental check

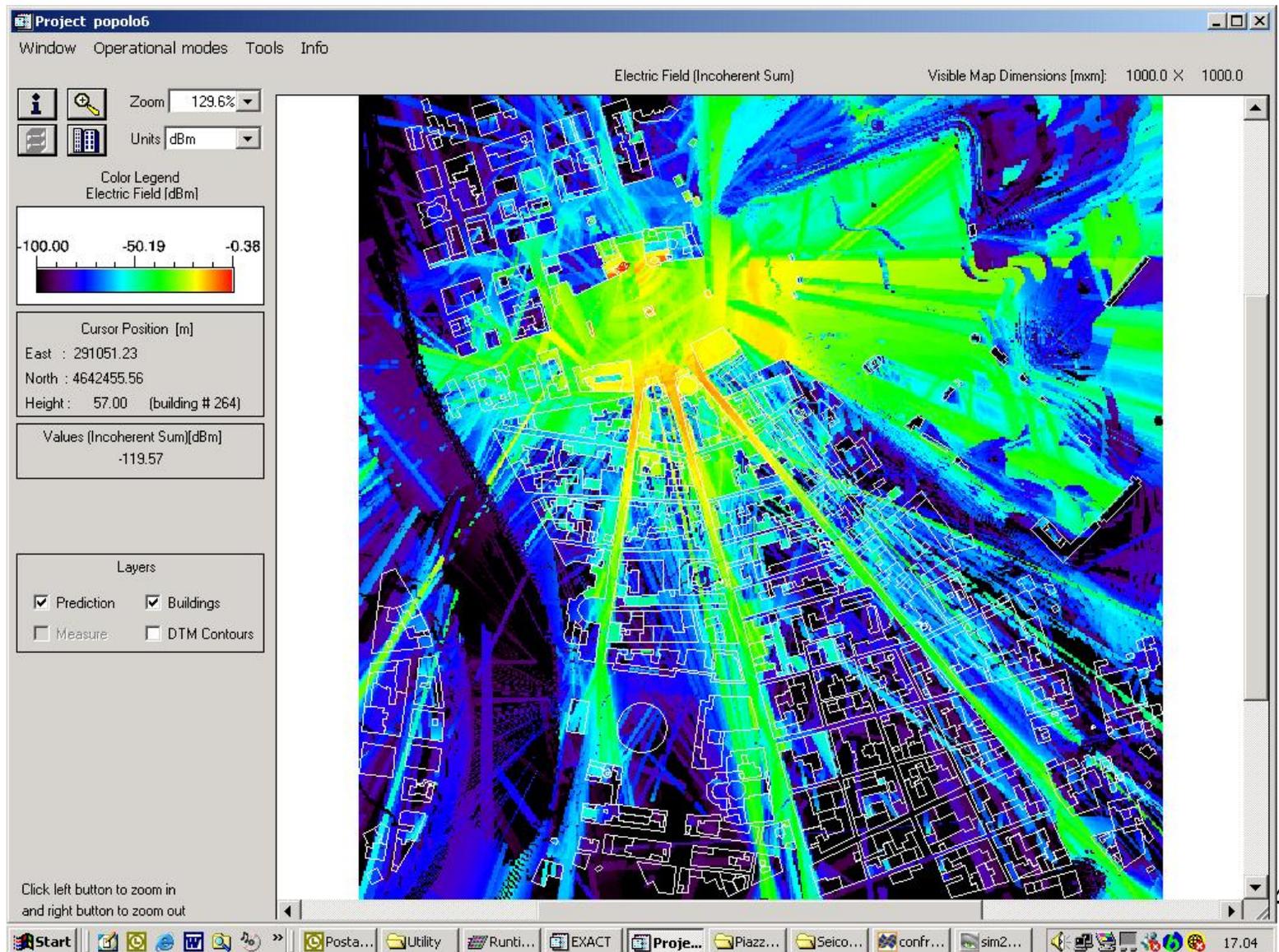
3-D false color simulation of the radiated field
[Piazza del Popolo and via del Corso, Rome, Italy]



DGM cnd.

Exp check cnd.

Corresponding 2-D false color representation of the radiated field



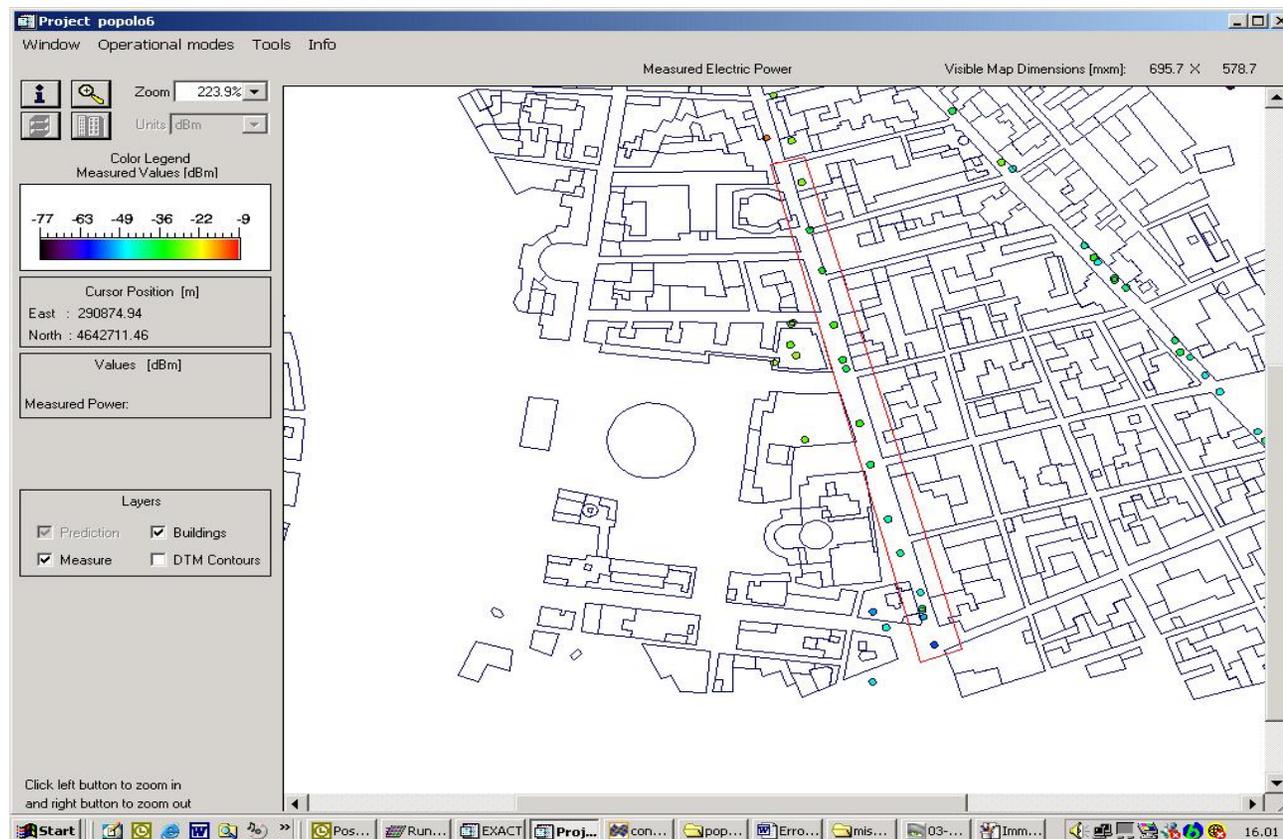
Comparison between measured and simulated field data

MEASURED VALUES [dBm]

- MIN -57.0
- MAX -26.0
- AVERAGE -38.8
- MEAN SQUARE DEV. 9.1

SIMULATED VALUES [dBm]

- MIN -48.5
- MAX -27.9
- AVERAGE -41.0
- MEAN SQUARE DEV. 6.2



Computational efficiency

- As rays progress, they generate reflected rays, emanating from virtual sources
- The number of virtual sources depends on the number and location of the buildings in the city
- If diffracted rays are ignored, the total number of virtual sources provides an estimate of the computational load
- At step 0, only the real source is present. At the subsequent step1, virtual sources are generated, each one generating further sources at step 2. And so on.
- As steps are increased, the intensity of the associate virtual sources decreases as well
- Additional sources may be neglected when the associated radiated field is below a threshold fixed by the sensitivity of the receiving devices

Computational efficiency cnd mathematical details

Equation: $(n_{i+1} - n_i) = \xi_i (n_i - n_{i-1})$

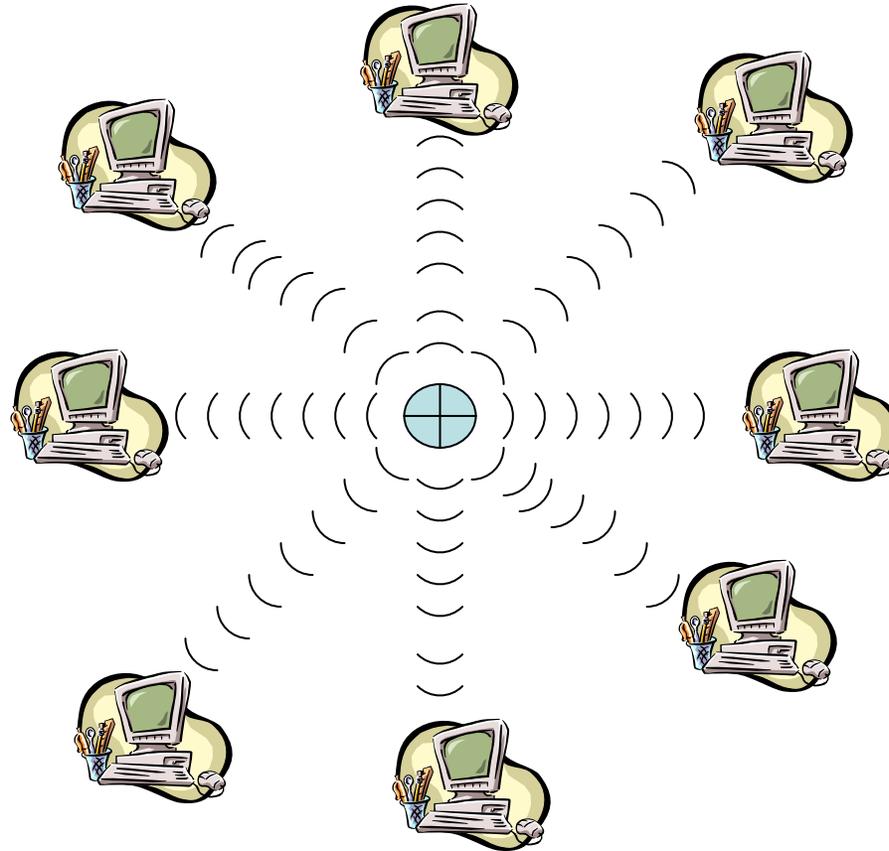
For $\xi_i = n_0 = \text{const} \Rightarrow n_i = n_0^i$

stopping at iteration I , total number of equivalent sources $n_I = n_0^I$

For $\xi_i = n_0^{\frac{1}{(1+\gamma i)^2}}$, $\gamma < 1 \Rightarrow n_i = n_0^{\frac{i}{1+\gamma i}}$

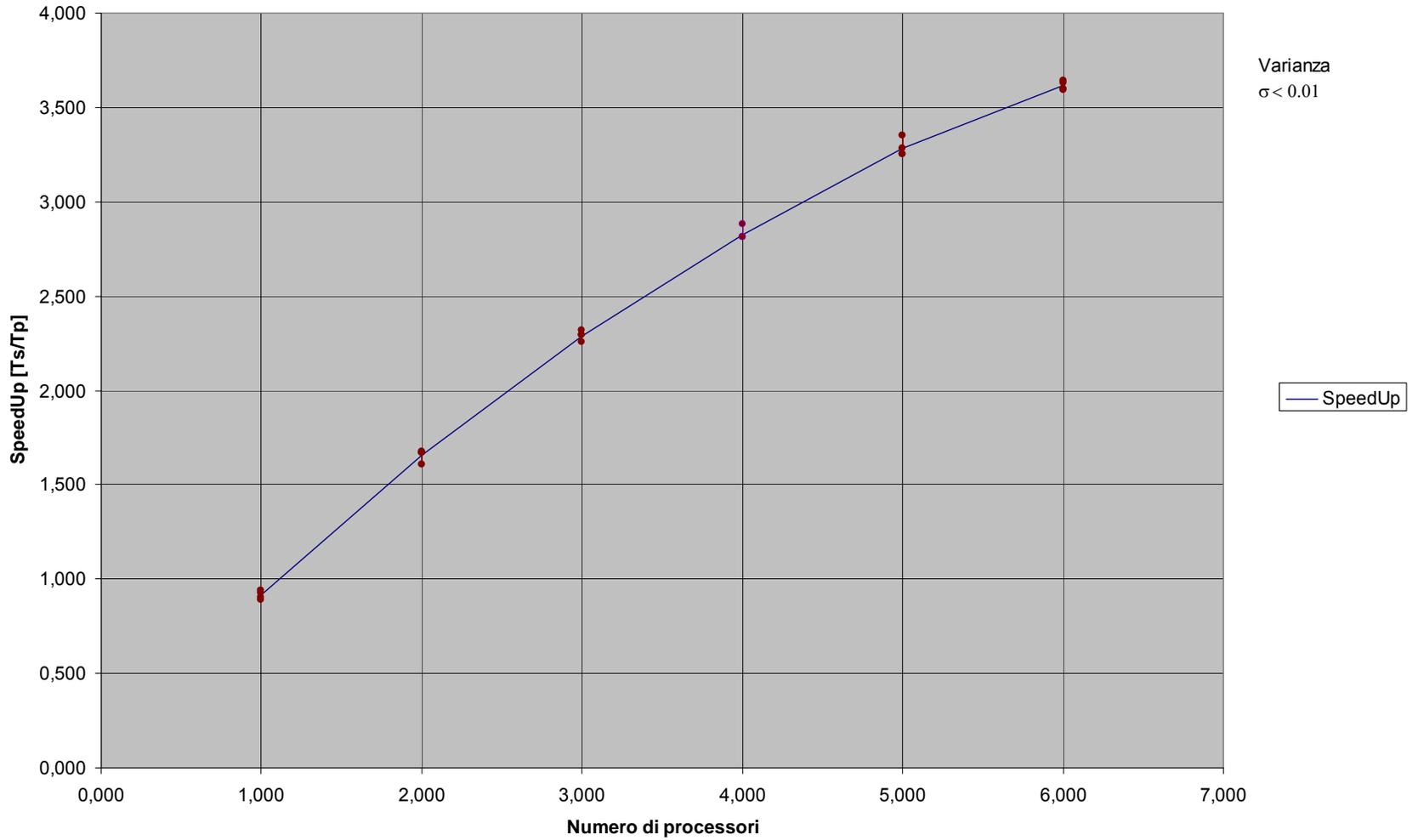
total number of equivalent sources $n_\infty = n_0^{\frac{1}{\gamma}}$

Parallelizzazione



Il procedimento seguito nella parallelizzazione è connaturale alla fisica del problema.

SPEED UP



The Stochastic Environment Model (SEM)

- At variance of DGM, a totally different philosophy is implemented in the frame of SEM
- Aim of the model is to derive *general analytical expressions*, describing the *average* properties of the urban propagation
- In addition, the analytical results are required to contain a *minimum number* of physically meaningful *parameters*
- This task may be pursued on along essentially *two lines of thought*: SESM AND SELM

➤ Stochastic Environment Small-scatterers Model (SESsM)

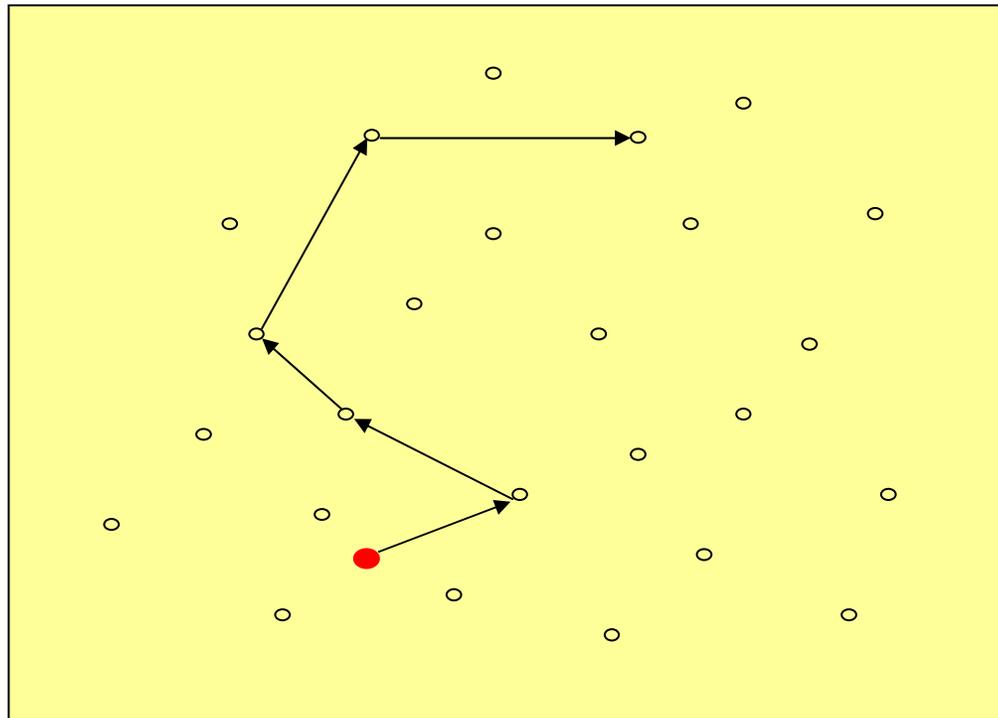
- SESsM: the scattering mechanism is dominated by myriads of small scatterers present in the city body

➤ Stochastic Environment Large-scatterers Model (SELSM)

- SELSM: the scattering mechanism is dominated by the urban tissue, organised as a percolative lattice

Stochastic Environment Small-Scatterers Model (SESsM)

Scattering mechanism dominated by myriads of small scatterers present in the city body



Propagation Model

- Electromagnetic propagation modeled as a bunch of photons emitted by the source (power summation implied)
- Pdf $q(r)$ of the injected photon to undergo its first hit at $P(r)$ given by

$$q(r) = \eta \frac{1}{4\pi r^2} \exp(-\eta r)$$

- Photons are absorbed with pdf $\alpha q(r)$ and scattered with pdf $(1-\alpha) q(r)$
- Average power loss equation

$$P_R = P_T \frac{G A}{4\pi r^2} C \exp(-br)$$

$$b = \left[1 - (1-\alpha)^2 \right] \eta$$

- Two basic parameters only:

$1/\eta$ = photon mean free path; α = absorption coefficient

Stochastic Environment

Small-scatterers Model features

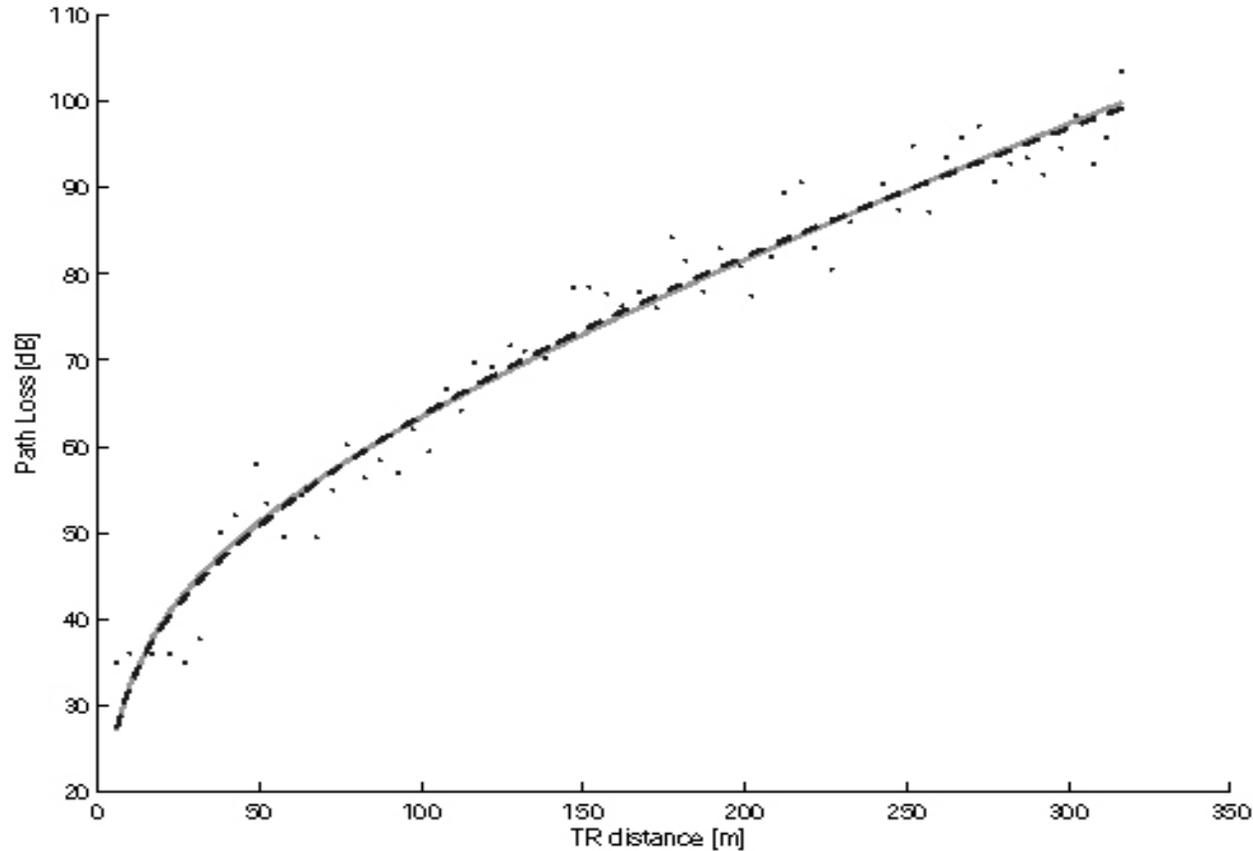
Attractive features

- The physical basis of the model is sound: propagation in the city streets undergoes a very large number of localised diffraction, due to people, cars, lamp posts, embellishments, etc.
- Only two physically sound parameters play a role: the collision mean free-path, $1/\eta$, related to the obstacles density; and the absorption coefficient, α , related to the scatterers electromagnetic properties
- This is at variance of heuristic expressions accounting for clutter attenuation

Limitations

- The geometric skeleton of the city is not imprinted in the model

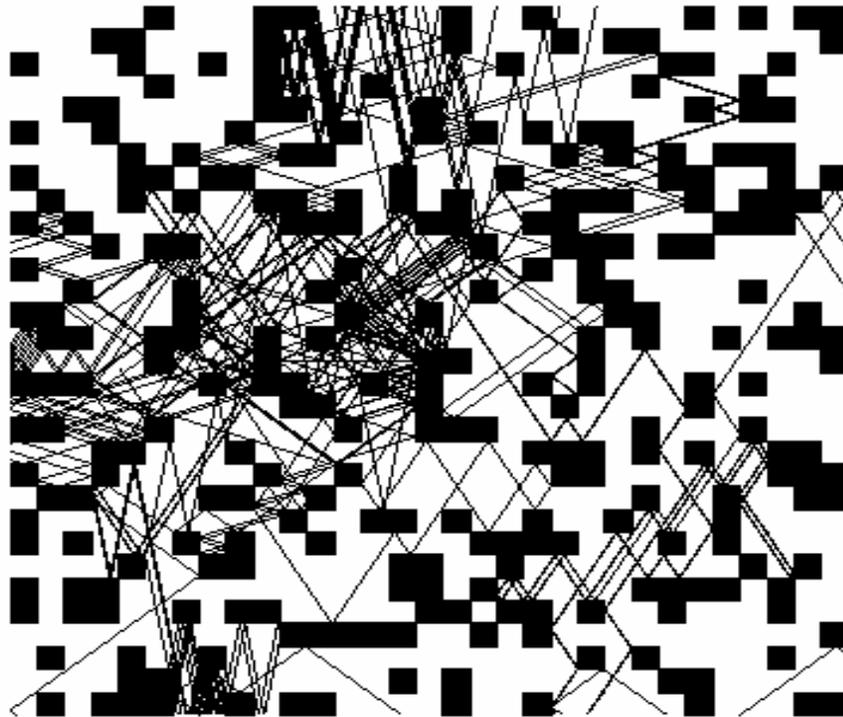
Experimental check



Average power loss vs. distance. Dots: experimental (averaged) values
Line: best fit interpolated formula with $\eta = 0.10$ [1/m] and $\alpha = 0.14$

Stochastic Environment Large– Scatterers Model (SELSM)

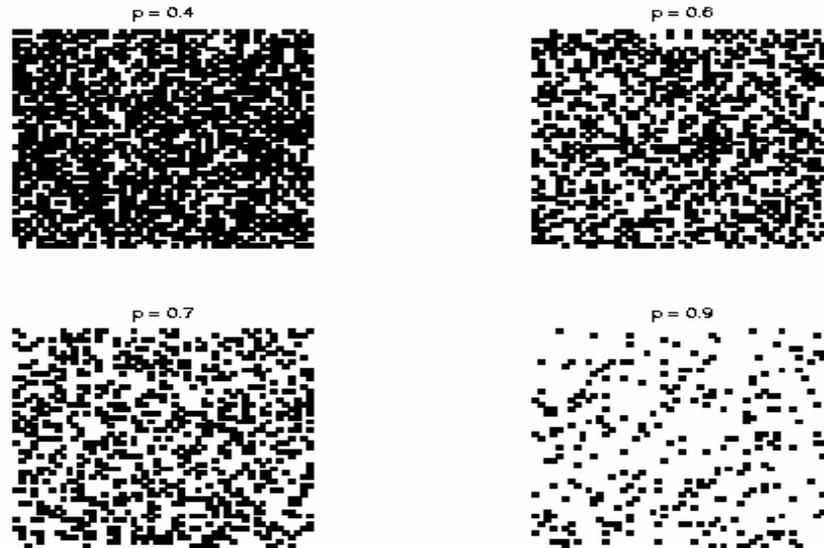
Scattering mechanism dominated by buildings,
modeled as a percolative lattice



[G. Franceschetti, R. Marano, F. Palmieri, "Wave propagation without wave equation. Toward an urban area model", IEEE Trans. Antennas Propagat., **47**, 1393-1404, 1999, recipient of APS Schelkunoff Award]

Propagation Model

- The city is modeled as a percolative lattice, where each site, of coordinate (m, n) , may be either empty with probability p or occupied with probability $q = (1-p)$.



- 2-D ray propagation is implemented, with diffraction neglected
- The expected value of the density power decay is similar to that found in the SSsC, but the correct metric is the *Manhattan* (or city block) *distance*, $|m|+|n|$, and not the usual Euclidean one

Stochastic Environment

Large-scatterers Model features

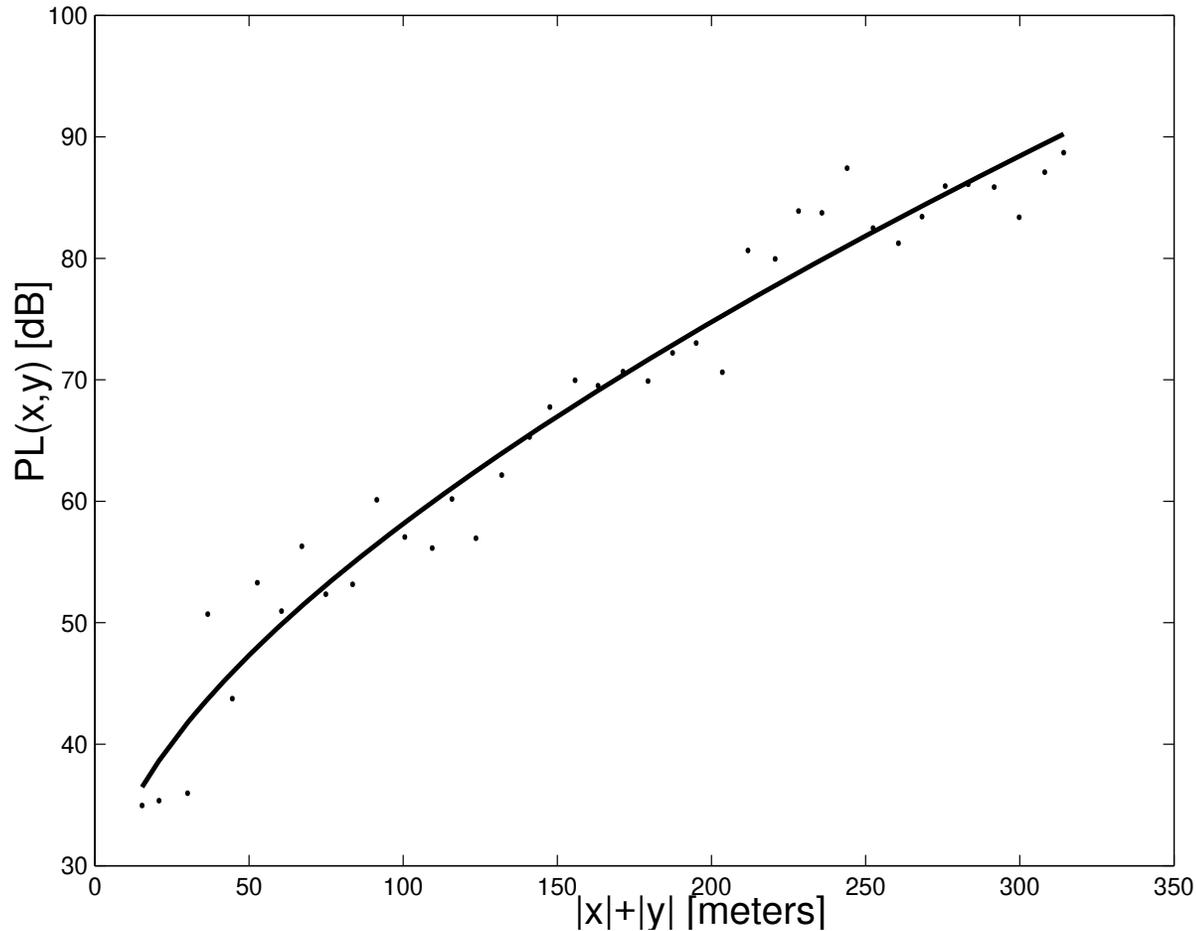
Attractive features

- The physical basis of the model is sound and the city structure is imprinted in the propagation mechanism, as testified by the introduction of the Manhattan distance

Limitations

- The model is two-dimensional
- Diffraction at occupied sites' edges is neglected

Experimental check



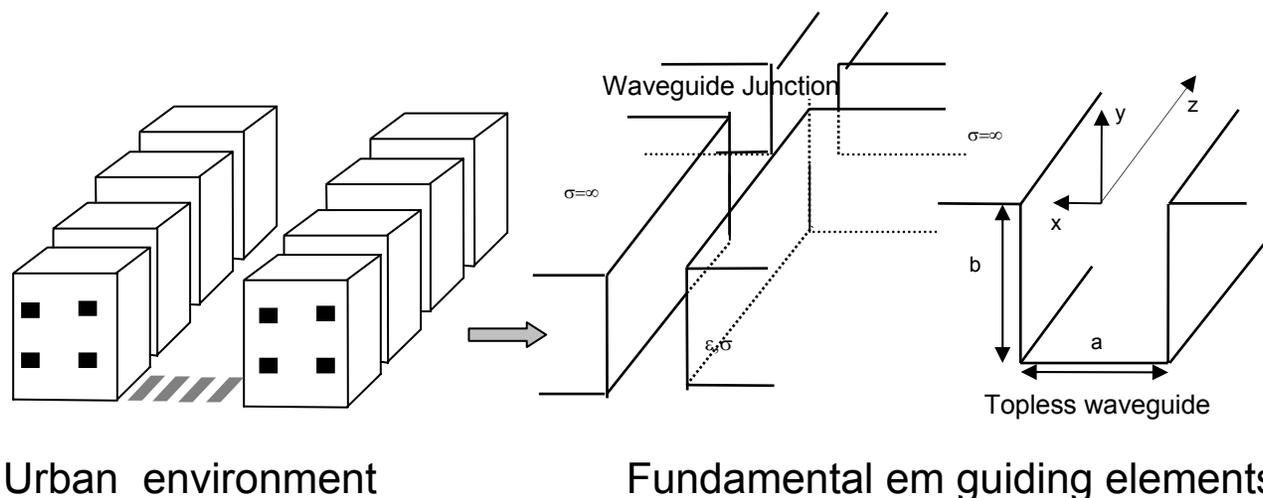
Average power loss vs. Manhattan distance. Dots: experimental (averaged) values. Line: best fit interpolated formula

The Next Step

- Can we explore alternative deterministic and/or stochastic models?
- May these models be more appropriate to new transmission wireless protocols? ...
- to the increasingly demanding use of microcells? ...
- to transmitting antennas at street level? ...

The Model Exploited

- A feature is missing in available models: the intrinsic guiding nature of the built up scenario, determined by the channelling nature of streets and their intersections
- A new model may be developed, finally leading to an equivalent planar circuit describing the guided propagation along the city



- This model seems to exhibit a solid rationale, is valid in general and particularly attractive for em excitation by means of radiators at the street level

Waveguiding Model (WGM)

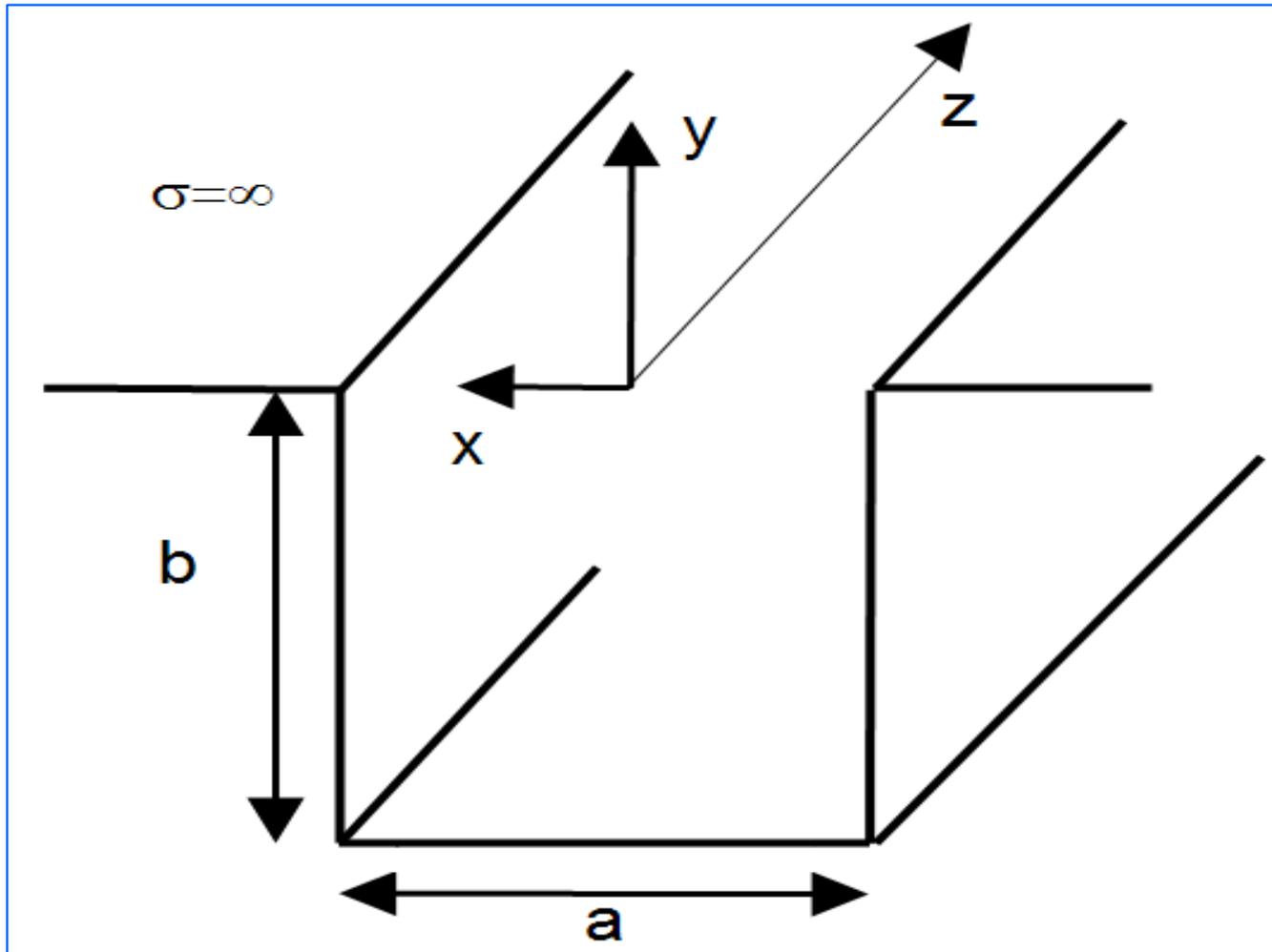
- Streets are schematised as overmoded waveguides with open ceiling (topless waveguides)
- Equivalent (coupled) transmission lines description is implemented
- Streets intersections and dead ends are modeled in terms of equivalent concentrated loads
- The final electromagnetic model of the city is a planar multimode net

The starting step

The simplest case of a straight street, bounded by buildings, with no intersection and of infinite length is considered



topless waveguide schematisation



perturbation procedure

■ Microwave background

Scalar modal functions

$$\nabla_T^2 \psi + k_T^2 \psi = 0 \quad k_T^2 = \left(\frac{m\pi}{a} \right)^2 + k_y^2$$

TE modes

$$\mathbf{E}_T(x, y, z) = \mathbf{e}(x, y) V(z) \quad \mathbf{H}_T(x, y, z) = \mathbf{h}(x, y) I(z)$$

$$i\omega\mu H_z = \nabla_T \cdot (\hat{\mathbf{z}} \times \mathbf{E}_T) = k_T V(z) \psi \quad \mathbf{h} = \hat{\mathbf{z}} \times \mathbf{e} = -\frac{1}{k_T} \nabla_T \psi$$

■ transverse (to y) fields, m even modes

$$\psi(x, y) = \sqrt{\frac{4}{ab[1 - \text{sinc}(2k_y b)]}} \cos[k_y(b + y)] \cos\left[\left(\frac{2m\pi}{a}\right)x\right], m = 1, \dots$$

$$\mathbf{E}(x, y, z) = -\frac{V(z)}{k_T} \frac{\partial \psi}{\partial y} \quad \mathbf{H}(x, y, z) = \frac{V(z)}{i\omega\mu} k_T \psi(x, y)$$

■ Elaboration

$$\iint dS [\psi \nabla_T^2 \psi + k_T^2 \psi^2] = 0 \Rightarrow k_T^2 = \iint dS \nabla_T \psi \cdot \nabla_T \psi - \int_{-a/2}^{a/2} \psi(x,0) \frac{\partial \psi}{\partial y} dx$$

$$E = -\frac{V(z)}{k_T} \frac{\partial \psi}{\partial y} \approx -\zeta_0 H = -\zeta_0 \frac{V(z)}{i\omega\mu} k_T \psi(x,y) \Rightarrow \frac{\partial \psi}{\partial y} = -i \frac{k_T^2}{k_0} \psi(x,y)$$

$$k_T^2 = \iint dS \nabla_T \psi \cdot \nabla_T \psi + i \frac{k_T^2}{k_0} \int_{-a/2}^{a/2} \psi^2(x,0) dx$$

.....

but $\iint dS \nabla_T \psi \cdot \nabla_T \psi = k_T^2$

perturbation procedure cnd

thus leading to the following

■ Iteration scheme

$$k_y^2 = k_y^2 + i \frac{k_T^2}{k_0} \frac{1}{b[1 - \text{sinc}(2k_y b)]} \cos^2(k_y b)$$

and in general

$$k_T^2 = k_T^2 + i \frac{k_T^2}{k_0} \int_{-a/2}^{a/2} \psi^2(x, 0) dx$$

iteration scheme exploited

- eigenvalue starting estimate

$$k_{m,n}^2 = \left(\frac{m\pi}{a}\right)^2 + \left(\frac{n\pi}{b}\right)^2$$

- compute the scalar modal function

$$\psi_{m,n}(x,0)$$

[or $\varphi_{m,n}(x, y)$ for TM-modes]

- compute the new eigenvalue

$$k_{m,n}^2 \longrightarrow k_{m,n}^2 + i \frac{k_T^2}{k_y} \int_{-a/2}^{a/2} \psi_{m,n}^2(x,0) dx$$

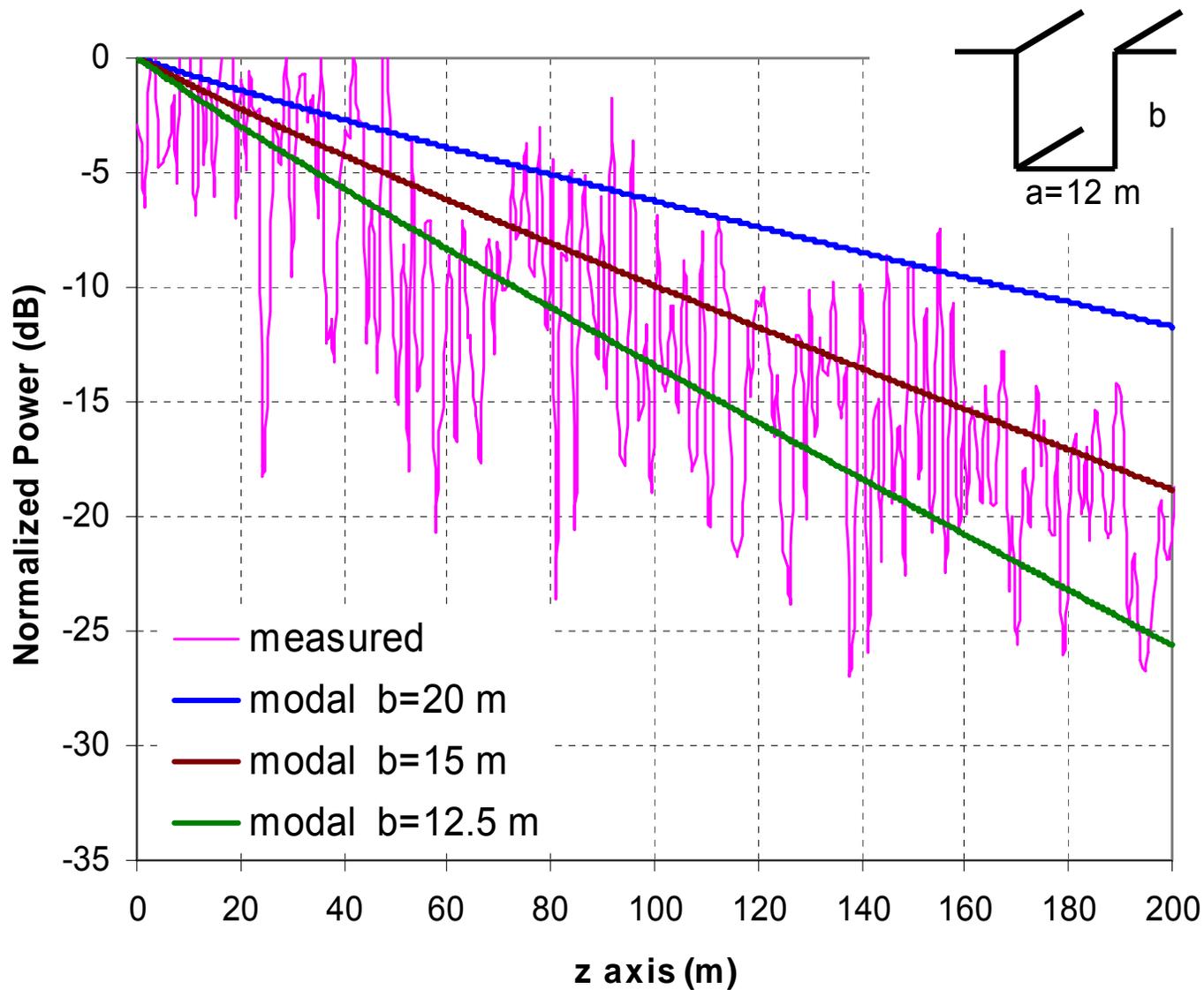
- iterate the procedure

- the topless-waveguide (m,n) mode propagation constant is given by

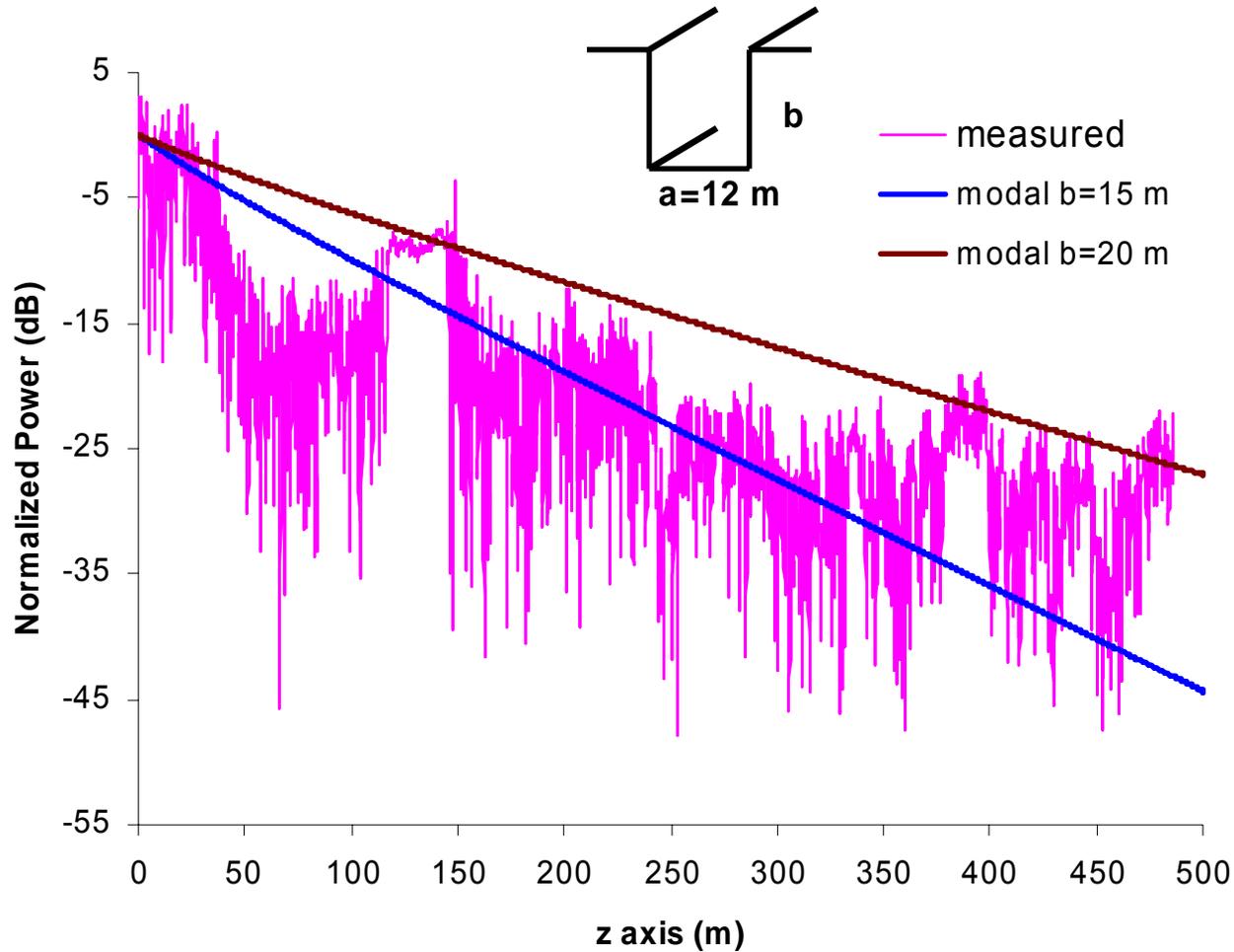
$$\beta_{n,m} = \sqrt{k_0^2 - k_{T n,m}^2}$$

- preliminary experiments are presented in the next slide

Experimental check



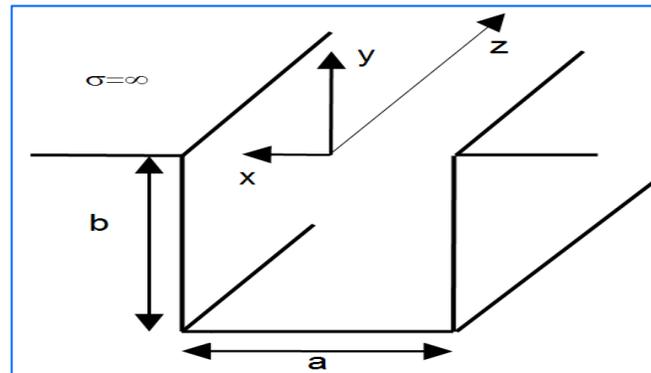
Additional experimental check



There is more than one way to skin a cat

Alternative theoretical approach

- geometry recalled



- x-polarised electric field, m even modes, transverse fields in the guide at $y=0$ [Kirchhoff approximation]

$$E_G(x,0) = A \cos\left(\frac{2m\pi}{a}x\right) \quad H_G(x,0) = \frac{1}{i\omega\mu} \frac{k_T^2}{k_y} \cotan(k_y b) E_G(x,0)$$

Alternative theoretical approach cnd

- plane wave expansion of the aperture field

$$\widehat{E}(u) = \frac{1}{2\pi} \int_{-a/2}^{a/2} E_G(x,0) \exp(iux) dx = \frac{4A}{\pi} (-)^m \frac{u \sin(ua/2)}{u^2 - (2m\pi/a)^2}$$

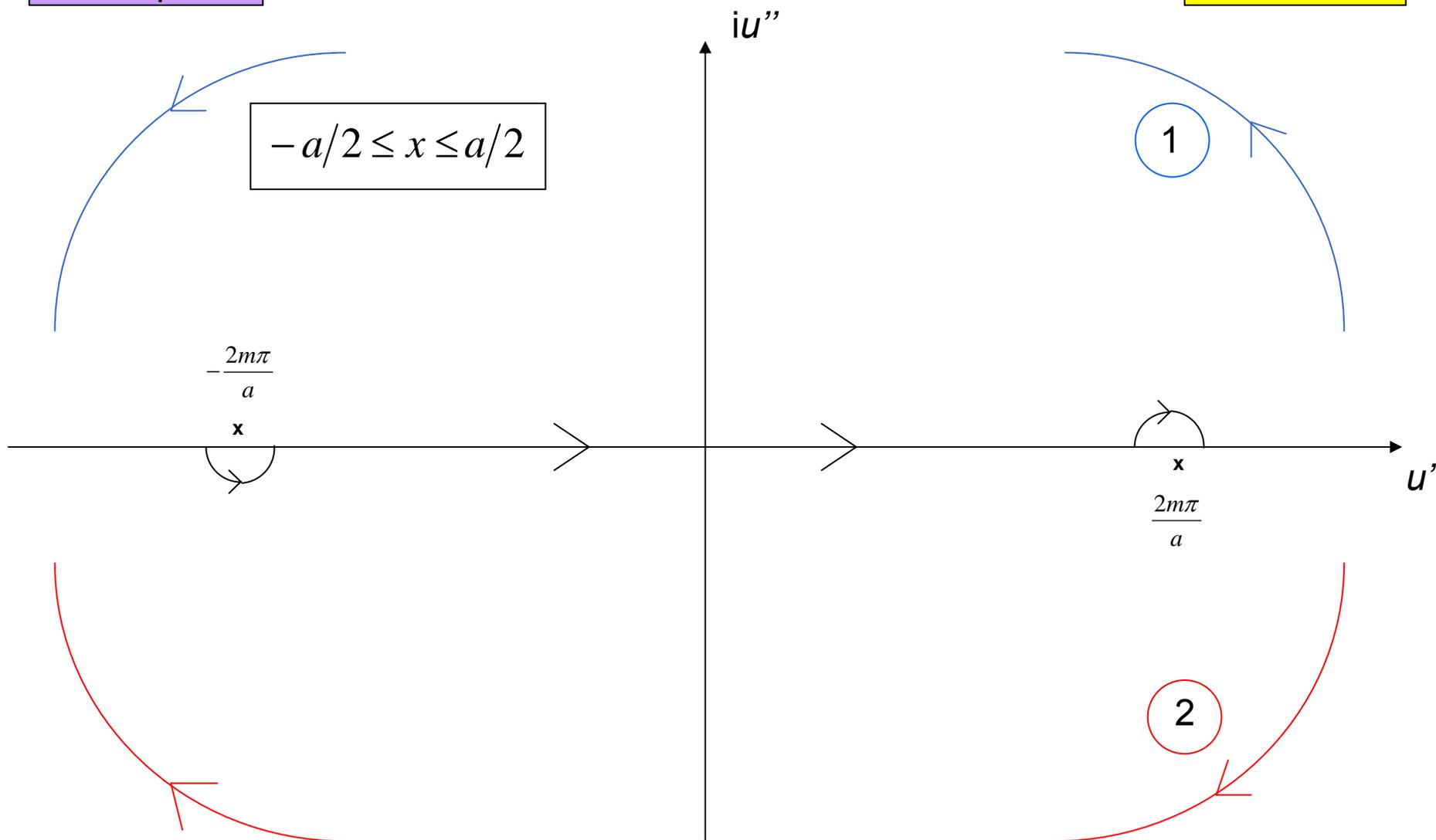
- transverse electric field in the half-space $y \geq 0$

$$\begin{aligned} E_{FS}(x, y) &= \int_{-\infty}^{\infty} \widehat{E}(u) \exp[-i(ux + vy)] du \\ &= \frac{4A}{2i\pi} (-)^m \int_{-\infty}^{+\infty} u \exp(-ivy) \frac{\exp[iu(a/2 - x)] - \exp[iu(a/2 + x)]}{[u - (2m\pi/a)][u + (2m\pi/a)]} du \\ &= \frac{4A}{2i\pi} (-)^m \int_{-\infty}^{+\infty} [\widehat{f}_1(u) + \widehat{f}_2(u)] du, \quad v^2 = k_0^2 - u^2 - \beta^2 = k_T^2 - u^2 \end{aligned}$$

NxStep cond

■ integration contours in the complex U -plane

AltAppr cond.



Complex $U = u' + iu''$ plane

Alternative theoretical approach cnd

- transverse electric field in the upper half-space $y \geq 0$, $-a/2 \leq x \leq a/2$

$$E_{FS}(x, y) = A \exp(-ik_y y) \cos\left(\frac{2m\pi}{a} x\right)$$

[tangential electric field is continuous by construction at the guide

open top: $E_G(x, 0) = E_{FS}(x, 0)$]

- transverse magnetic field in the upper half-space $y \geq 0$, $-a/2 \leq x \leq a/2$

$$H_{FS}(x, y) = \frac{1}{i\omega\mu} \frac{\partial E_{FS}}{\partial y} = -\frac{ik_y}{i\omega\mu} A \exp(-ik_y y) \cos\left(\frac{2m\pi}{a} x\right) = -\frac{k_y}{\omega\mu} E_{FS}(x, y)$$

Alternative theoretical approach cnd

- electric fields at $y=0$ in the guide and in free-space are continuous by construction

$$E_G(x,0) = E_{FS}(x,0)$$

- enforcement of transverse magnetic field continuity

$$H_G(x,0) = H_{FS}(x,0)$$

leads to the dispersion equation

$$iZ_0 \tan(k_y b) + \left[\frac{k_T^2 k_0}{k_y^3} \right] \zeta_0 = 0$$

in the unknown eigenvalue k_y

Model Features

- Model of (downtown) urban area as a planar (overmoded) microwave net seems very appropriate
- Scattering matrixes of the junctions must be developed
- Improvement of the guide model is possible: walls with finite conductivity and guide with a “human plasma” bottom layer could be exploited
- Most of energy radiated by the base stations on top of the buildings is reflected toward the open space by the neighboring building roofs. Alternative location of base stations at street level is most appropriate to this model
- Synchronized propagation is perhaps possible