- 2023-08-23
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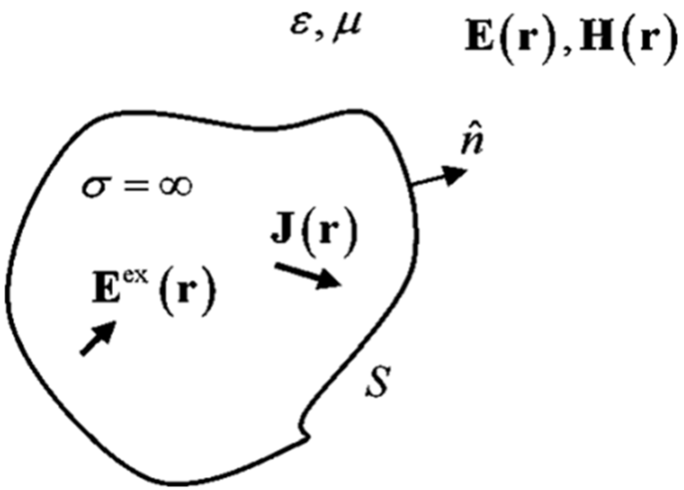
전자장 데이터 기반의 전류분포 모델링: 극소 다이폴 모델링

Outline

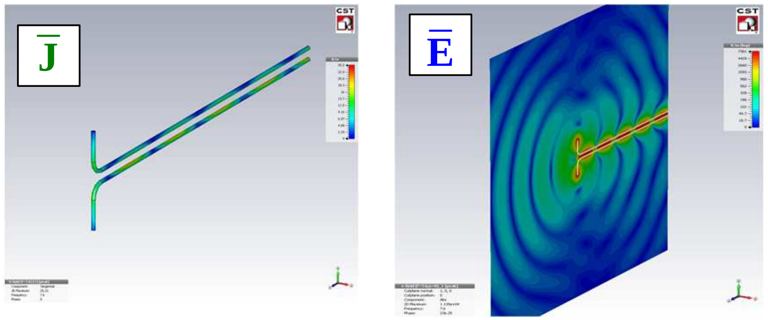
전류분포 모델링: 극소다이폴 모델링

전류분포와 Free-space Green’s function

- how to calculate radiated field from current distribution?
- through **Free-Space Green’s Function (FSGF)**
- $\mathbf{E}^{ex}$ (incident field) → $\mathbf{J}$ (induced current) → $\mathbf{E}$, $\mathbf{H}$ (radiated field)



transmitting mode analysis using FSGF



$$\bar{\mathbf{E}}(\mathbf{r}) = \int_S ds' \bar{\mathbf{G}}(\mathbf{r}, \mathbf{r}') \cdot \bar{\mathbf{J}}(\mathbf{r}')$$

$\bar{\mathbf{J}}$ → $\bar{\mathbf{G}}$ → $\bar{\mathbf{E}}$

antenna current distribution | FSGF | radiation electric field

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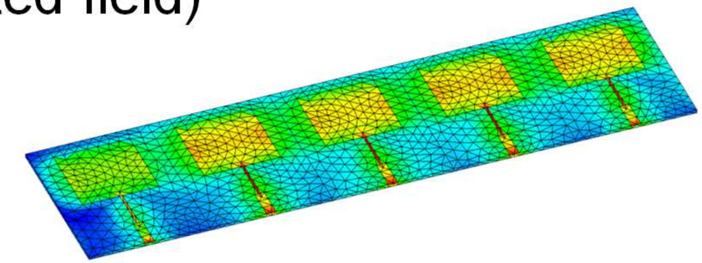
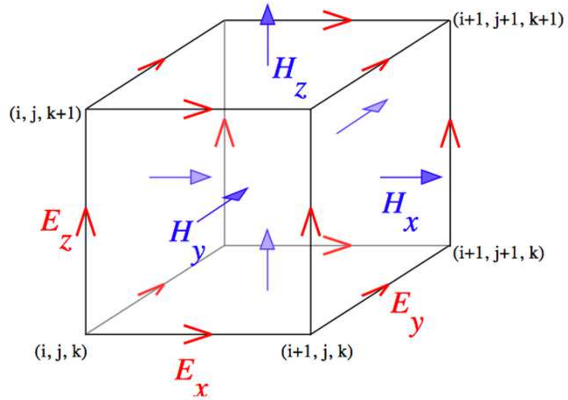
전류분포 모델링: 극소다이폴 모델링

전류분포와 Free-space Green's function

- $\mathbf{E}^{inc}$ (incident field) → $\mathbf{J}$ (induced current) → $\mathbf{E}$, $\mathbf{H}$ (radiated field)
- the most time, memory, cost-consuming process
- 전류 분포는 어떻게 구할까?
  - analytical: solving electromagnetic problems
  - numerical: full-wave methods (MoM, FEM, FDTD, …) or high-freq. methods (PO, GO, UTD, GTD, …)
  - 대부분의 실제 문제들은 numerical methods 활용



MoM (Moment method)



FDTD (Finite-Difference Time-Domain)

전류분포 모델링: 극소다이폴 모델링

전류분포와 Free-space Green's function

- 고주파수 대역 활용 → electrical dimension 증가
- 회로 및 소자의 복잡도 증가 → finer segmentation 필요
- **기술 발전** → numerical method의 계산 복잡도 증가

- *따라서, 기존 numerical method의 대안 필요*

전류분포 모델링: 극소다이폴 모델링

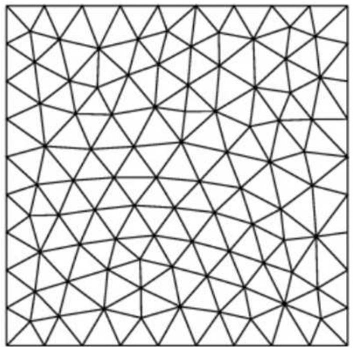
NURBS*: Non-Uniform Rational Basis Spline

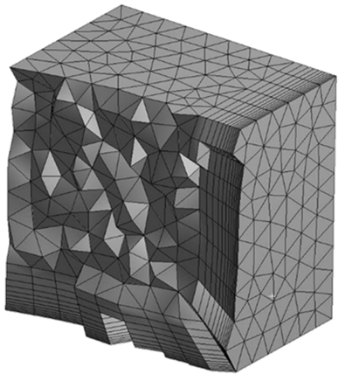
전류분포와 Free-space Green’s function

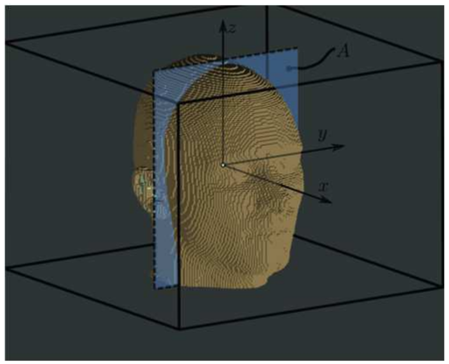
- numerical method를 통한 전류분포의 exact solution?

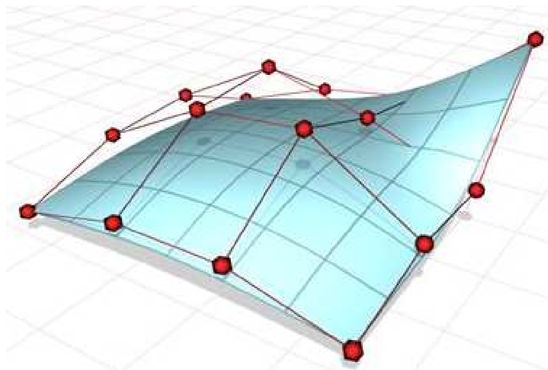
Numerical method	Segmentation model
MoM	triangular or tetrahedron mesh
FDTD	rectangular voxel
PO, PTD	NURBS*

- 결국 solution은, *‘induced current model’*







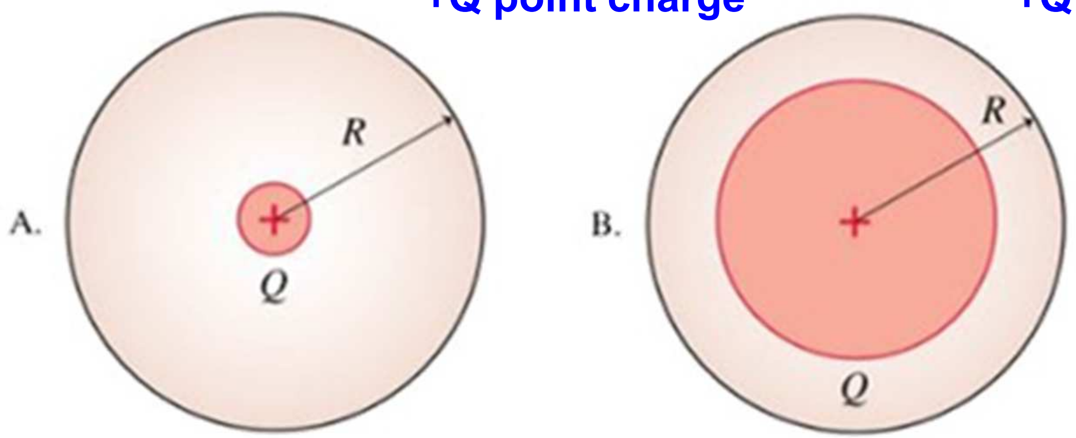


전류분포와 Free-space Green's function

- Ex) Gauss' law
  - same field distribution outside the boundary
  - **same** radiated field → **different** current model (O)
  - **same** current model → **different** radiated field (X)

+Q point charge

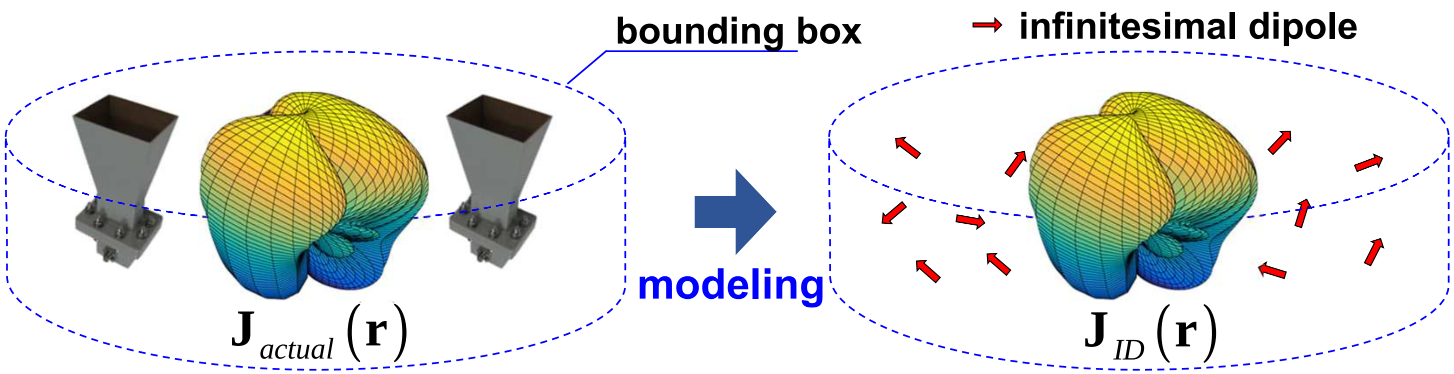
+Q charged sphere



전류분포 모델링: 극소다이폴 모델링

Basic concept of infinitesimal dipole modeling (IDM)

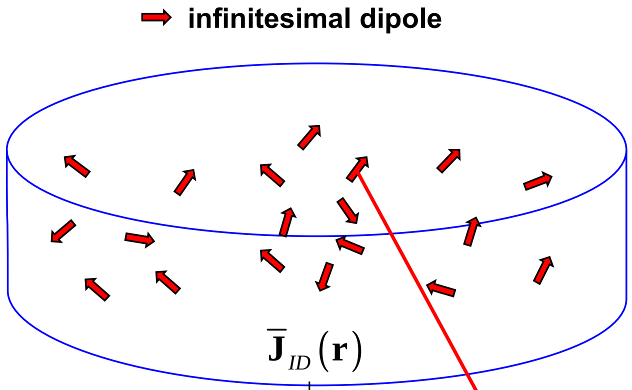
- $\mathbf{E}^{inc}$ (incident field) → $\boxed{\mathbf{J}\text{ (induced current)} \rightarrow \mathbf{E}, \mathbf{H}\text{ (radiated field)}}$
- radiated field로부터 induced current를 역추적
- 일종의 reverse engineering
- 최적화 된 IDM = an induced current model



전류분포 모델링: 극소다이폴 모델링

Basic concept of infinitesimal dipole modeling (IDM)

- variables of infinitesimal dipoles
  - position (3) + excitation coefficients (2) + orientation (2) = 7 variables

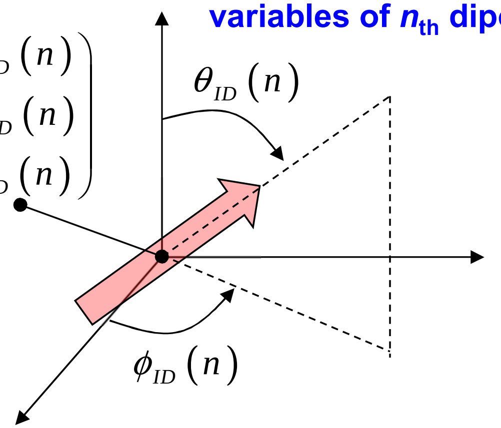


$$\mathbf{J}_{ID}(\mathbf{r}) = \sum_{n=1}^{N} \mathbf{p}_n \delta\left(\mathbf{r} - \mathbf{r}_n^{ID}\right)$$

a set of infinitesimal dipoles
(a set of point current sources)

variables of n_{th} dipole

$$\mathbf{r}_n^{ID} = \begin{pmatrix} x_{ID}(n) \\ y_{ID}(n) \\ z_{ID}(n) \end{pmatrix}$$



$$\mathbf{p}_n = \boxed{A_{ID}(n) \cdot e^{j\psi_{ID}}} \cdot \begin{pmatrix} \cos\left(\boxed{\phi_{ID}(n)}\right)\sin\left(\boxed{\theta_{ID}(n)}\right) \\ \sin\left(\phi_{ID}(n)\right)\sin\left(\theta_{ID}(n)\right) \\ \cos\left(\theta_{ID}(n)\right) \end{pmatrix}$$

dipole moment of
n_{th} dipole

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전류분포 모델링: 극소다이폴 모델링

Basic concept of infinitesimal dipole modeling (IDM)

- near and far-field of IDM
  - near-field

dipole moment

$$\mathbf{E}(\mathbf{r}) = \sum_{n=1}^{N} \frac{1}{4\pi\omega\varepsilon_0} \left[\boxed{k^2} \left(\left(\mathbf{n}_n \times \boxed{\mathbf{p}_n} \right) \times \mathbf{n}_n \right) \frac{e^{-jkr_n}}{\boxed{r_n}} + \left(3\mathbf{n}_n \left(\mathbf{n}_n \cdot \mathbf{p}_n \right) - \mathbf{p}_n \right) \left(\frac{jk}{r_n^{\ 2}} + \frac{1}{r_n^{\ 3}} \right) e^{-jkr_n} \right]$$

0

$$\boxed{\mathbf{n}_n} = \left(\frac{x - x_{ID}(n)}{r_n}, \frac{y - y_{ID}(n)}{r_n}, \frac{z - z_{ID}(n)}{r_n} \right)^T = \frac{\mathbf{r} - \mathbf{r}_n^{ID}}{\left| \mathbf{r} - \mathbf{r}_n^{ID} \right|} \qquad \boxed{r_n} = \left| \mathbf{r} - \mathbf{r}_n^{ID} \right|$$

unit vector from ID to observation point

distance between ID and observation point

  - far-field
    - using far-field approximation

$\mathbf{n}_n \rightarrow \hat{\mathbf{r}}$

① path differences (positions)

$$\mathbf{E}(\mathbf{r}) = \sum_{n=1}^{N} \frac{1}{4\pi\omega\varepsilon_0} \left[k^2 \boxed{\left(\left(\hat{\mathbf{r}} \times \mathbf{p}_n \right) \times \hat{\mathbf{r}} \right)} \boxed{e^{jk\mathbf{r}_n^{ID} \cdot \hat{\mathbf{r}}}} \frac{e^{-jk\mathbf{r}}}{r} \right]$$

② excitation coefficients and polarizations

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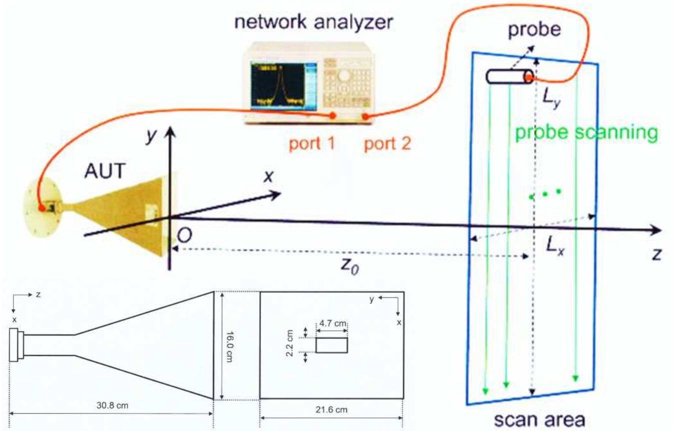
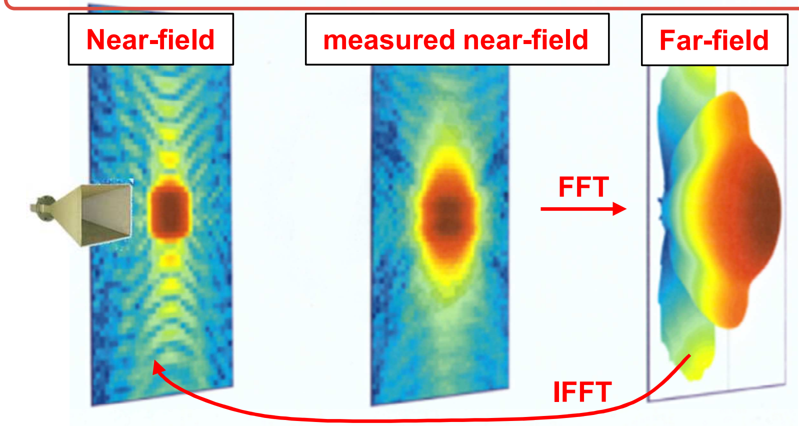
전류분포 모델링: 극소다이폴 모델링

Infinitesimal dipole modeling vs. Fourier transform

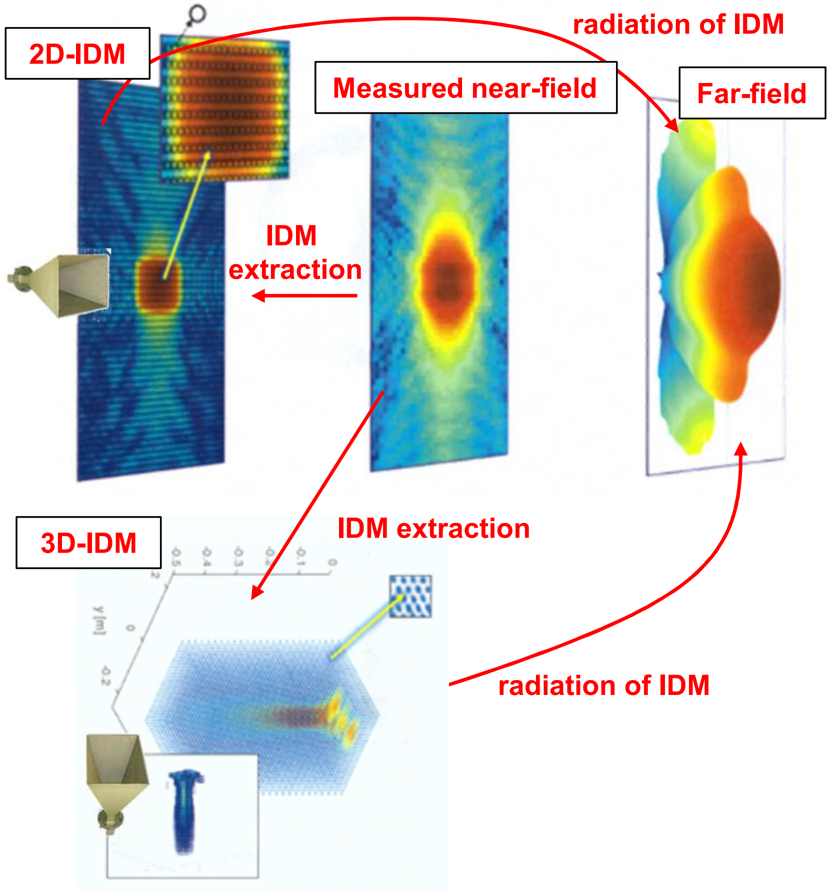
Near-field measurement of Horn antenna



FFT based field transform



IDM based field transform



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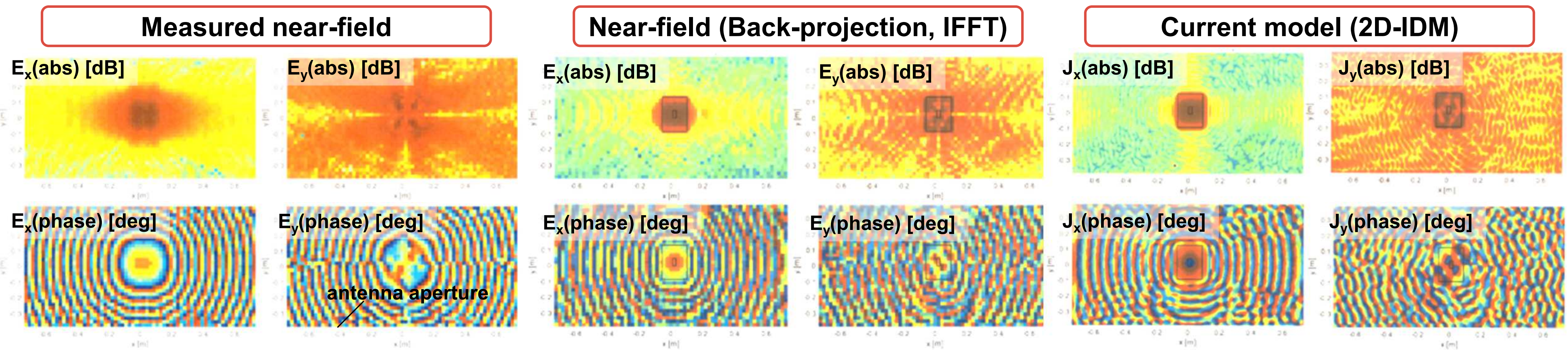
전류분포 모델링: 극소다이폴 모델링

Infinitesimal dipole modeling vs. Fourier transform

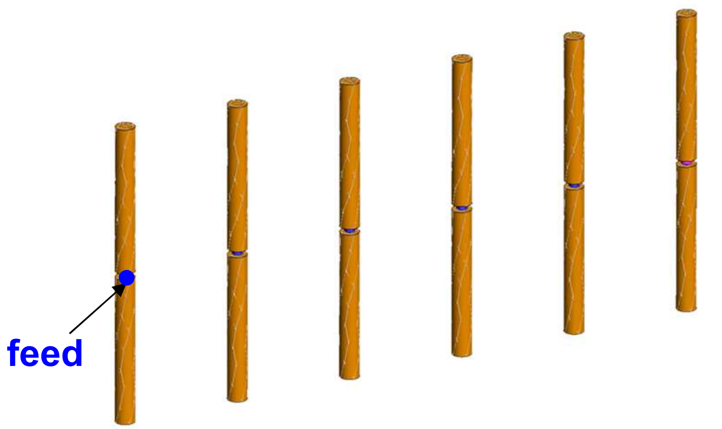
- 결과적인 물리량의 차이
- Fourier transform-based projection → field transform (signal processing)
- IDM-based projection → **induced current model (electromagnetics)**



전류분포 모델링: 극소다이폴 모델링

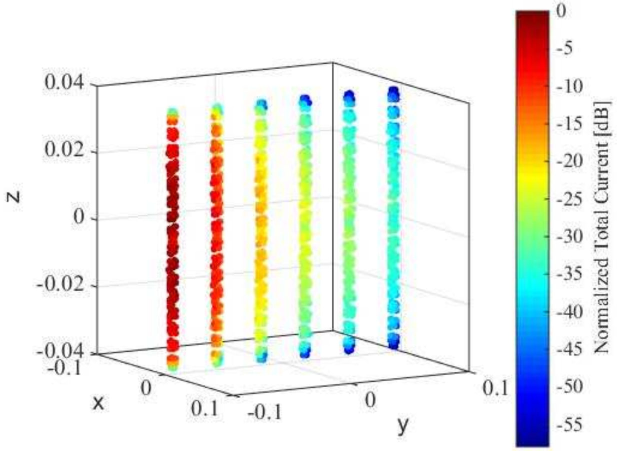
Verification of infinitesimal dipole modeling (IDM)

- **visual** similarity of current distribution
- MoM vs. IDM
- Ex 1) dipole array antenna



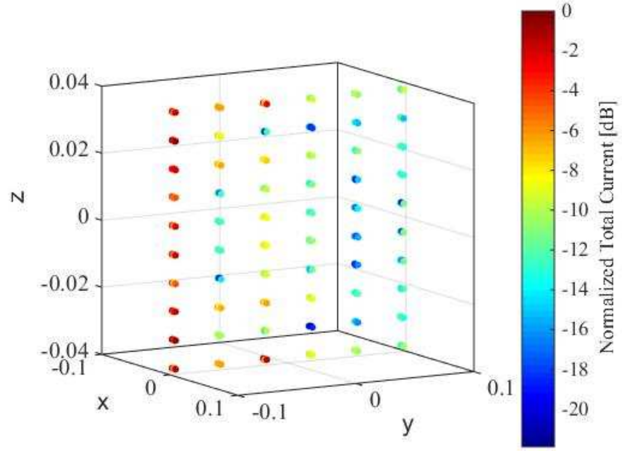
dipole array antenna

# of triangular mesh = 960



current model (MoM)

# of infinitesimal dipoles = 240

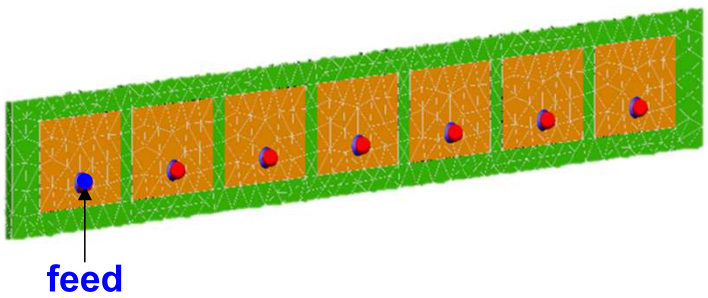


current model (IDM)

전류분포 모델링: 극소다이폴 모델링

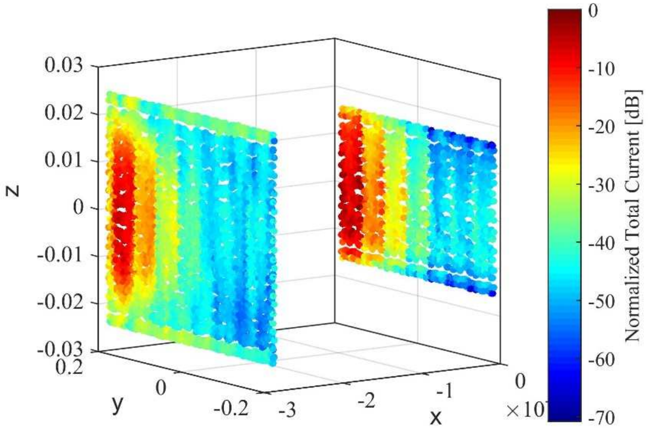
Verification of infinitesimal dipole modeling (IDM)

- **visual** similarity of current distribution
- MoM vs. IDM
- Ex 2) patch array antenna



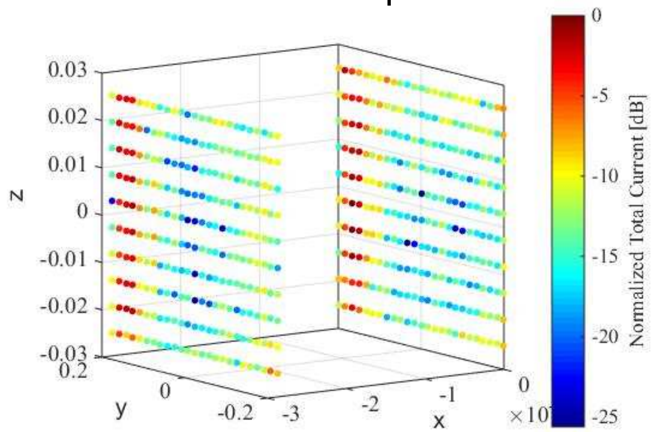
patch array antenna

# of triangular mesh = 4754



current model (MoM)

# of infinitesimal dipoles = 500



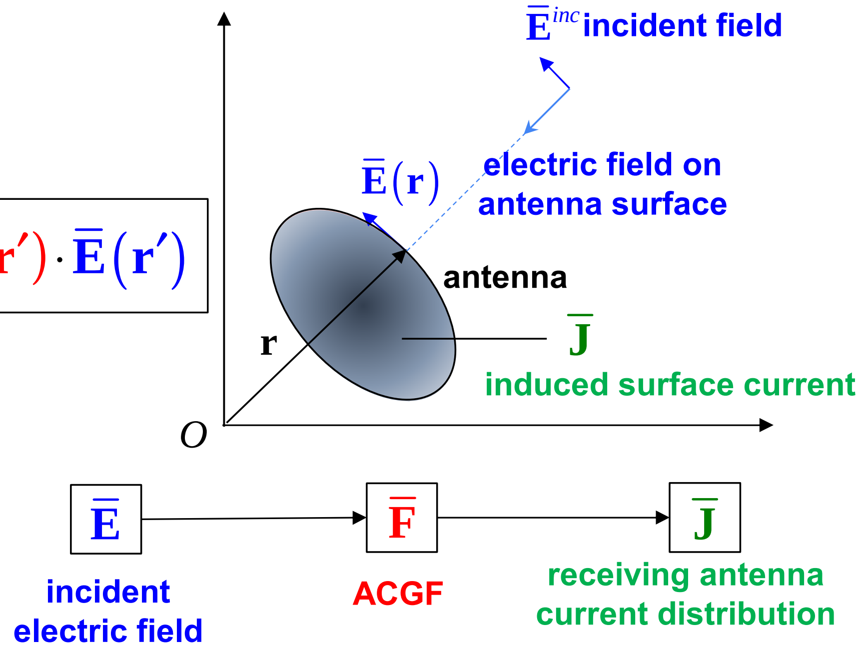
current model (IDM)

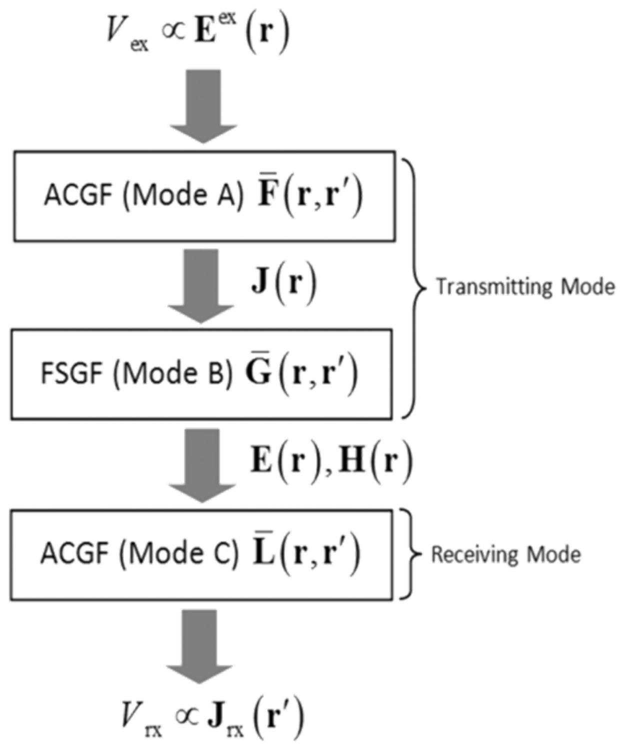
Antenna Current Green's Function (ACGF)

: **impulse response** represented as **antenna current distribution** with **impulse electric field excitation**

receiving mode anlaysis using ACGF

$$\bar{\mathbf{J}}(\mathbf{r}) = \int_S ds' \,\bar{\mathbf{F}}(\mathbf{r},\mathbf{r}') \cdot \bar{\mathbf{E}}(\mathbf{r}')$$





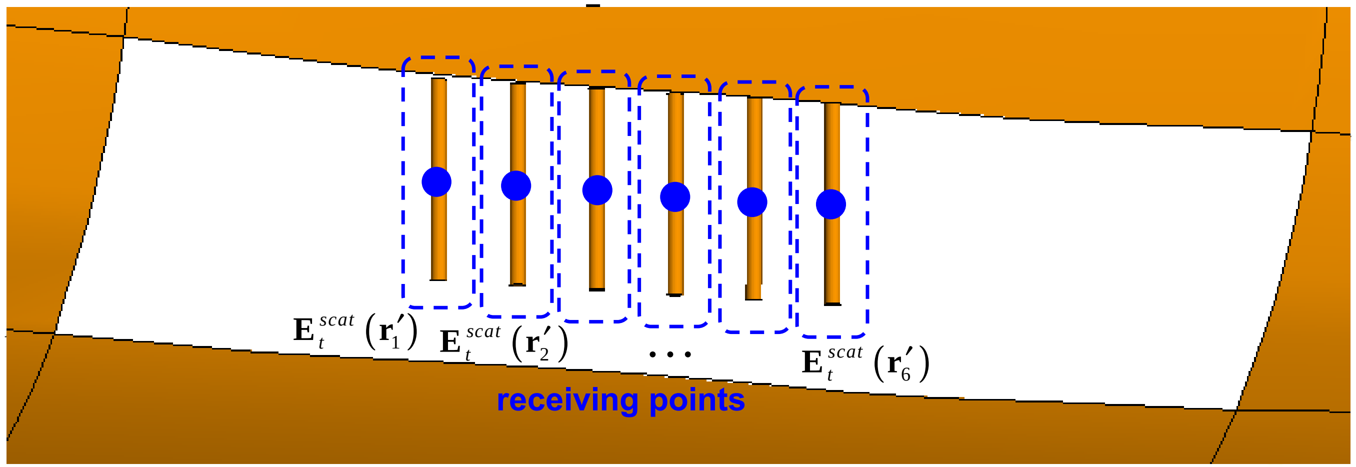
극소다이폴 모델의 검증

IDM은 ACGF로써 활용될 수 있을까?

- 산란파 수신 환경에서의 능동소자패턴 계산

scattered field on receiving point

$$v(\mathbf{r}'_m) \approx -\frac{Z_L Z_{ANT}}{Z_L + Z_{ANT}} \left\{ \sum_{n=1}^{N} \sum_{k=1}^{K} \overline{\mathbf{F}}^{a}_{nm}(\mathbf{r}_k, \mathbf{r}'_m) \cdot \boxed{\mathbf{E}^{dir}_t(\mathbf{r}_k)}\, ds_k + \sum_{n=1}^{N} \overline{\mathbf{F}}^{a}_{nm}(\mathbf{r}'_n, \mathbf{r}'_m) \cdot \boxed{\mathbf{E}^{scat}_t(\mathbf{r}'_n)}\, S_n \right\}$$



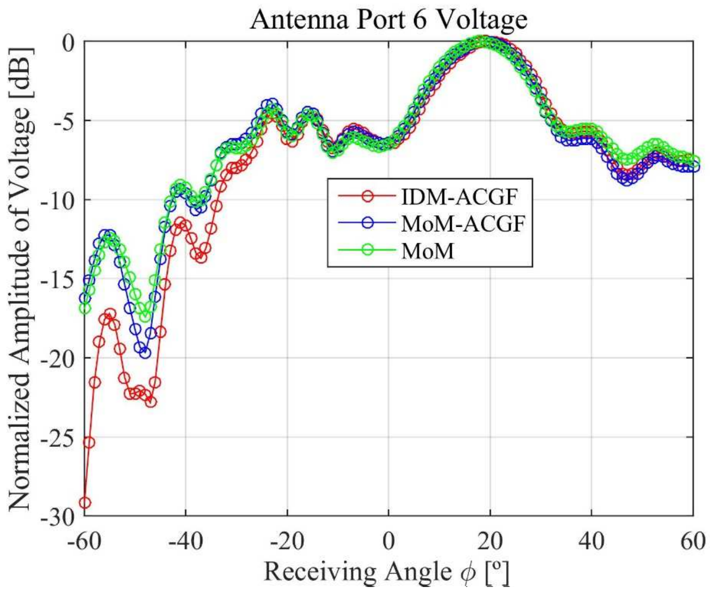
incident direction
polarized dirction

IDM은 ACGF로써 활용될 수 있을까?

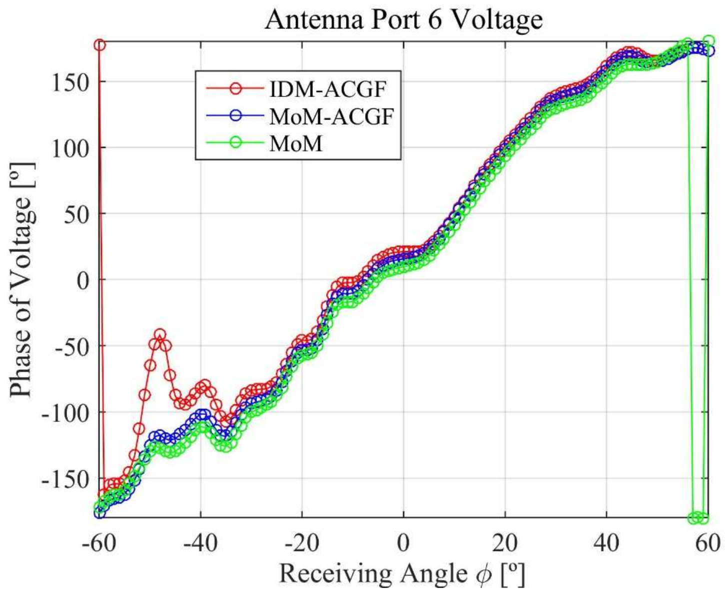
- 산란파 수신 환경에서의 능동소자패턴 계산

scattered field
on receiving point

$$v(\mathbf{r}'_m) \square -\frac{Z_L Z_{ANT}}{Z_L + Z_{ANT}} \left\{ \sum_{n=1}^{N} \sum_{k=1}^{K} \overline{\mathbf{F}}^{a}_{nm}(\mathbf{r}_k, \mathbf{r}'_m) \cdot \boxed{\mathbf{E}^{dir}_t(\mathbf{r}_k)} ds_k + \sum_{n=1}^{N} \overline{\mathbf{F}}^{a}_{nm}(\mathbf{r}'_n, \mathbf{r}'_m) \cdot \boxed{\mathbf{E}^{scat}_t(\mathbf{r}'_n)} S_n \right\}$$



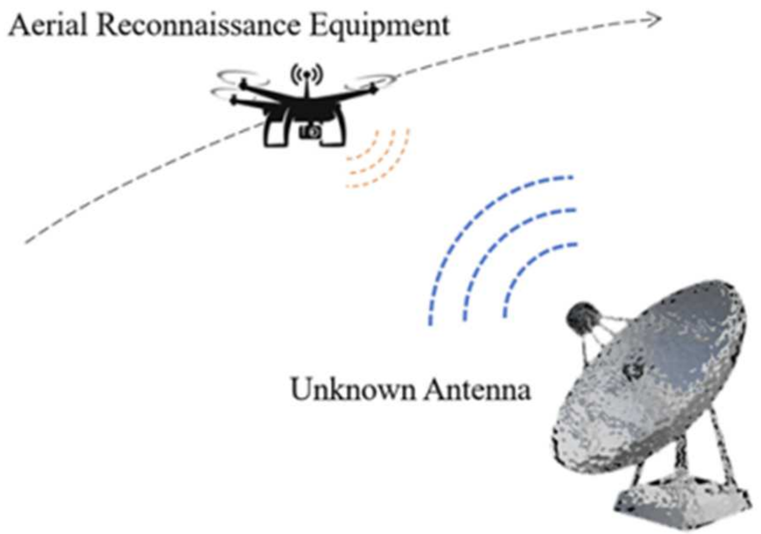
calculated & measured AEP (amplitude)
(ϕ = 105˚, θ = -60˚ : 1˚ : 60˚)

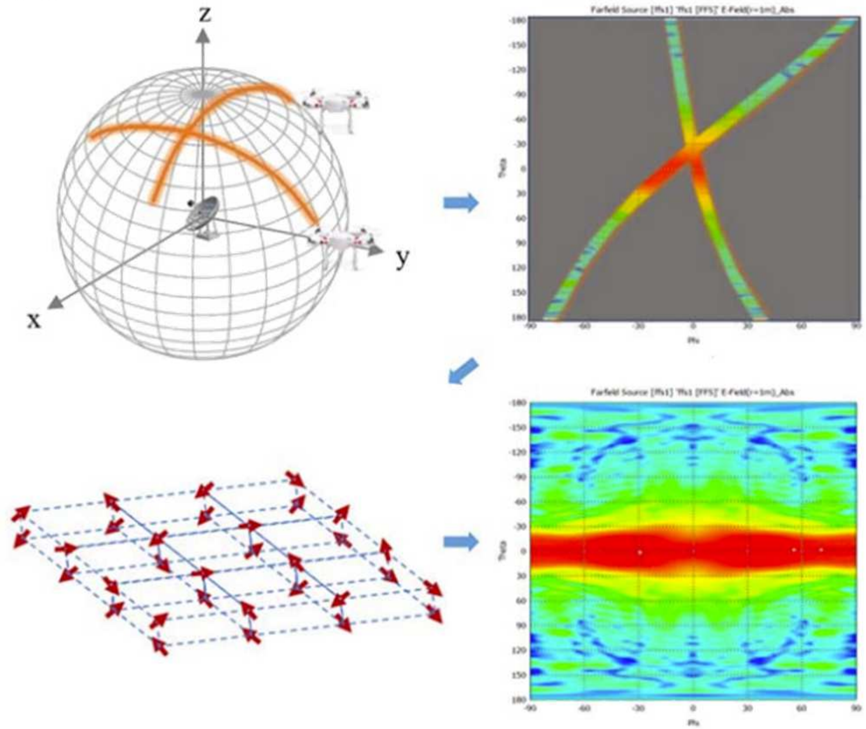


calculated & measured AEP (phase)
(ϕ = 105˚, θ = -60˚ : 1˚ : 60˚)

Transformation of radiated field

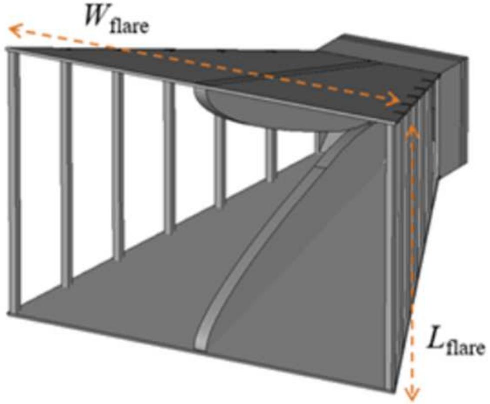
- Sparse far-field patterns → Full-coverage of far-field data
- EM characteristics of the unknown antenna

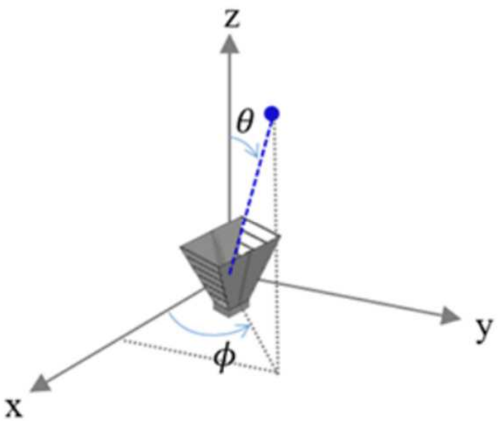


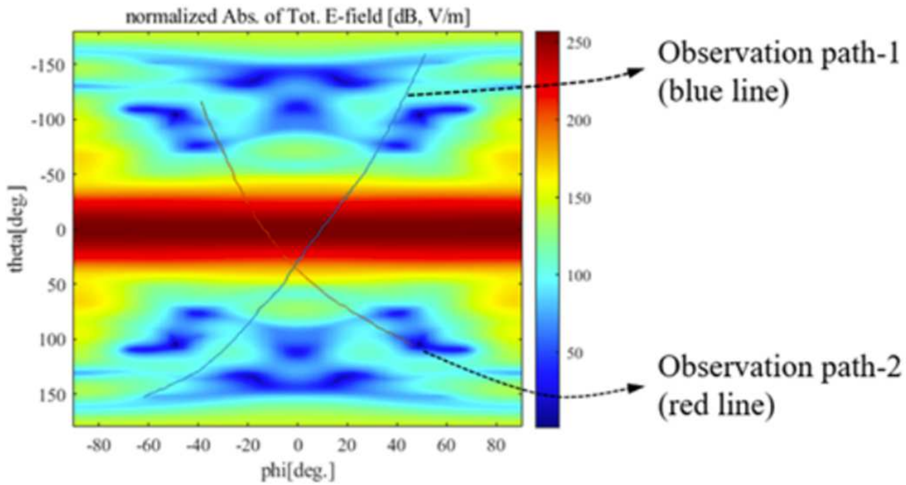


Transformation of radiated field

- simulation: single-horn antenna (2.4 GHz)
- observed far-field: 1-D angular domain → used to obtain IDM



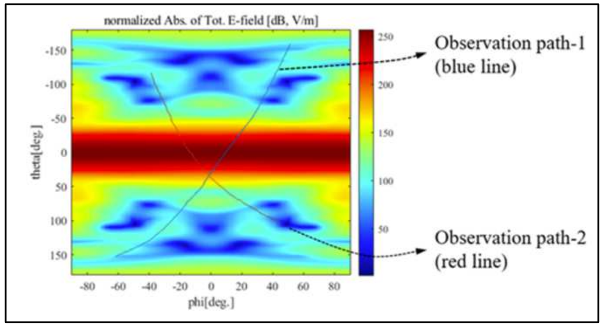


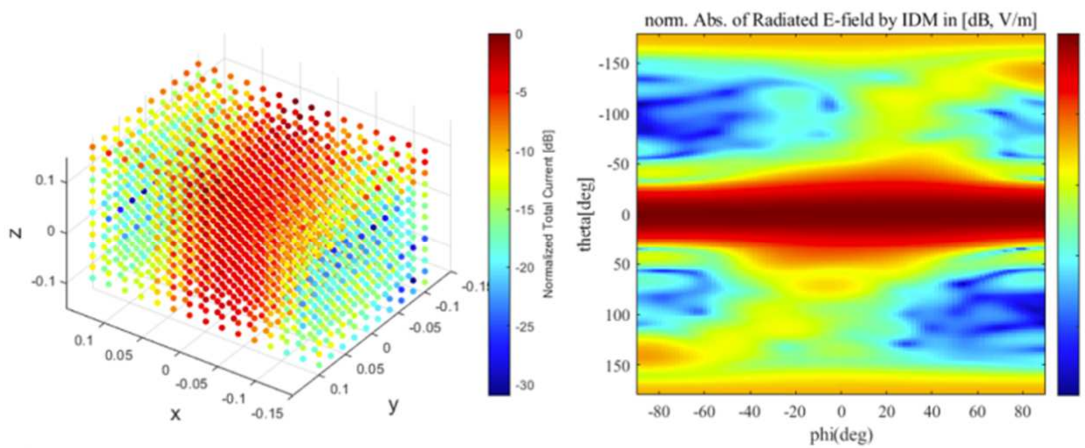


극소다이폴 모델의 응용

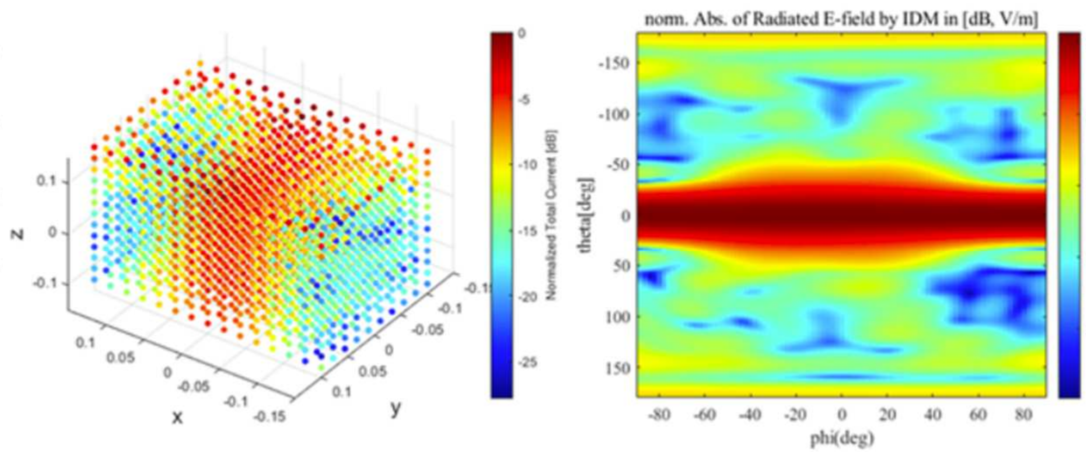
Transformation of radiated field

- simulation: single-horn antenna (2.4 GHz)
- two different source data → two different results
- *“modeling에 활용된 radiated field의 power portion → modeling accuracy”*





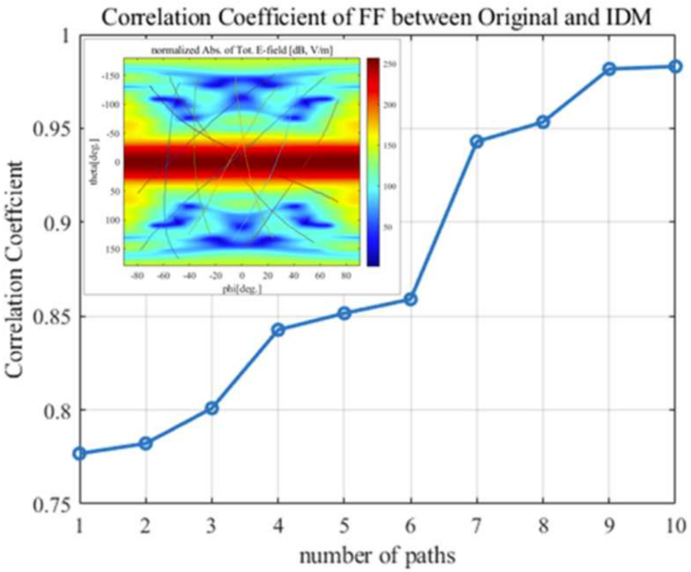
(a)

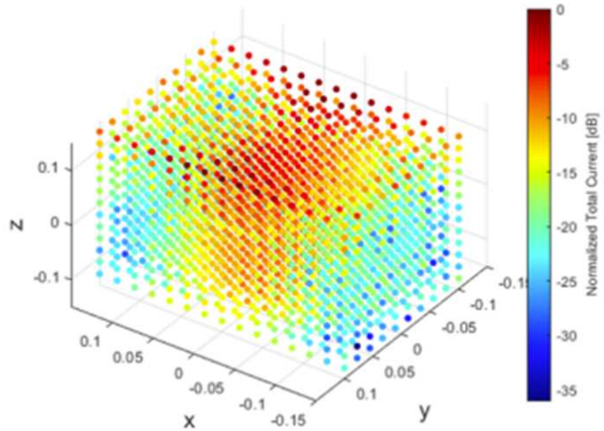


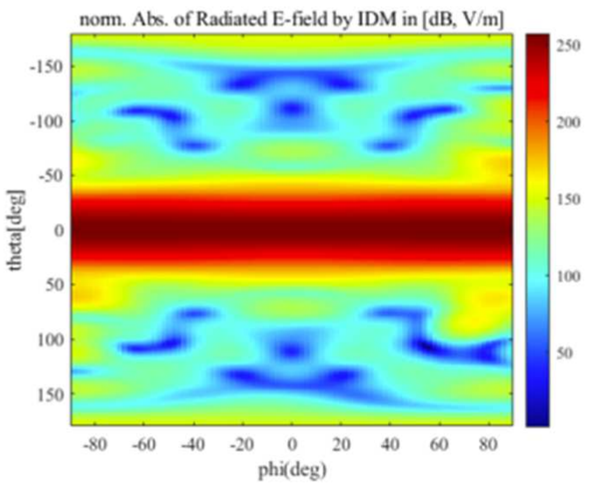
(b)

Transformation of radiated field

- simulation: single-horn antenna (2.4 GHz)
- *the more source data, the more accurate modeling*







IDM 개발 및 발전 방향

- noise와 field accuracy에 대한 sensitivity 정립
- modeling 정확도 개선 (실제 current distribution과의 일치도 향상)
- IDM to current reconstruction / optimization 성능 개선
- 최종 목표: 비접촉 방식의 전류분포 추정