Training Session
On Antenna Measurement
Ph. Garreau

Prepared by
Prof. J. Ch. Bolomey, Supélec & Dr. Ph. Garreau, Satimo
Consultancy Program, 2004

AGENDA

- **Part 1 – EM background**

- Part 2 – Antenna Measurement

- Part 3 – Near-Field Techniques

PART 1
EM BACKGROUND FOR ANTENNA CHARACTERIZATION

- OBJECTIVES
- INTRODUCTION TO ANTENNA CHARACTERIZATION
- THE TRANSMISSION MODE
- THE RECEIVING MODE
- THE ANTENNA AS AN ANGULAR LINEAR FILTER
- CONCLUSIONS

OBJECTIVES 1 / 2

- ANTENNA BASICS FOCUSED ON CHARACTERIZATION TECHNIQUES

- NEW CHARACTERIZATION TECHNIQUES ARE REQUIRED TO FACE WITH AN INCREASING COMPLEXITY OF ANTENNAS, IN TERMS OF:
  – STRUCTURE,
  – FONCTIONALITY
  – ENVIRONMENT

OBJECTIVES 2 / 2

- A SIGNIFICANT ELECTROMAGNETIC BACKGROUND, INVOLVING APPROPRIATE CONCEPTS AND FORMULATIONS, IS REQUIRED FOR:
  - *UNDERSTANDING* ADVANCED ANTENNA CHARACTERIZATION TECHNIQUES
  - *DEVELOPPING* A COMPREHENSIVE AND QUANTITATIVE ANALYSIS OF THESE TECHNIQUES
  - *COMPARING* THESE TECHNIQUES TO MORE STANDARD APPROACHES
  - *SELECTING* AND *OPTIMIZING* THE MOST APPROPRIATE TECHNIQUE FOR A SPECIFIC APPLICATION (e.g. VEHICLE COMMUNICATION)

THE ANTENNA AS AN INTERFACE

ELECTRONIC CIRCUIT

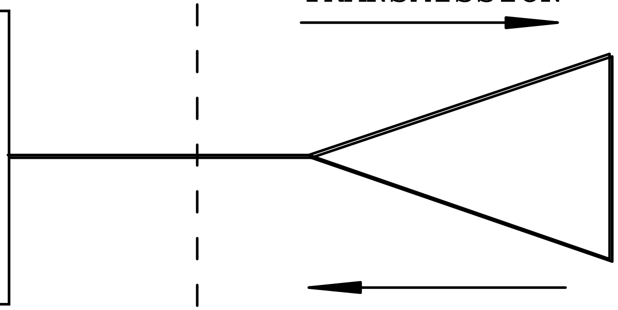
COMPONENTS,
GUIDING
STRUCTURES,
ETC

VOLTAGE,
CURRENT,
IMPEDANCE,
TRANSFER FONCTION,
ETC…

SIGNALS…
UNDER CONTROL

ANTENNA

TRANSMISSION



RECEPTION

PROPAGATION SPACE

"FREE-SPACE",
FLAT GROUND,
SHARP MOUNTAIN,
URBAN,
INTRA-MUROS,
ETC…

EM FIELD DISTRIBUTION
(NEAR TO FAR),
GLOBAL QUANTITIES

WAVES…
OUT OF CONTROL

INTRODUCTION TO ANTENNA CHARACTERIZATION
PRELIMINARY REMARKS 1/2

- TRANSMITTING AND RECEIVING MODES ARE (USUALLY) RELATED VIA RECIPROCITY

- BOTH MODES MAY BE INVOLVED IN ANTENNA CHARACTERIZATION
  - TRANSMITTING MODE: NEAR-FIELD FACILITY
  - RECEIVING MODE: LONG & COMPACT RANGES

- IN CHARACTERIZATION TECHNIQUES, FREE SPACE ENVIRONMENT PLAYS A PARTICULARLY IMPORTANT (REFERENCE) ROLE:
  - (RELATIVELY) EASY TO REALIZE
  - CONSTITUTES A REALISTIC SIMPLIFICATION OF LINE OF SIGHT TRANSMSISSION MODALITIES
  - PROVIDES MOST OF THE QUANTITIES REQUIRED FOR PREDICTIONS IN MORE COMPLEX ENVIRONMENTS

INTRODUCTION TO ANTENNA CHARACTERIZATION
PRELIMINARY REMARKS 2/2

- ANTENNA CHARACTERIZATION CAN BE PERFORMED VIA:

  - NUMERICAL MODELING

  - EXPERIMENTS (DIRECT APPROACH)

  - COMBINING MEASUREMENTS AND PROCESSING (INDIRECT APPROACH)

INTRODUCTION TO ANTENNA CHARACTERIZATION
NUMERICAL MODELING VS EXPERIMENT

NUMERICAL MODELING

- APPLY TO MODELS
- NEEDS CODE + COMPUTER FOR CALCULATING
  FIELD DISTRIBUTION, CURRENT,
  IMPEDANCE ...
- CODE LIMITATIONS
  (STRUCTURE, DIMENSION, FREQUENCY BAND,...)
- COMPUTER LIMITATIONS
  (TIME, MEMORY)
- FLEXIBILITY IN:
  - MOVING THE OBSERVATION POINT
  - CHANGING PARAMETERS
  - INVESTIGATING SENSITIVITIES
  - MODIFYING EXCITATIONS
- REQUIRED FOR DESIGN OPTIMIZATION

EXPERIMENT

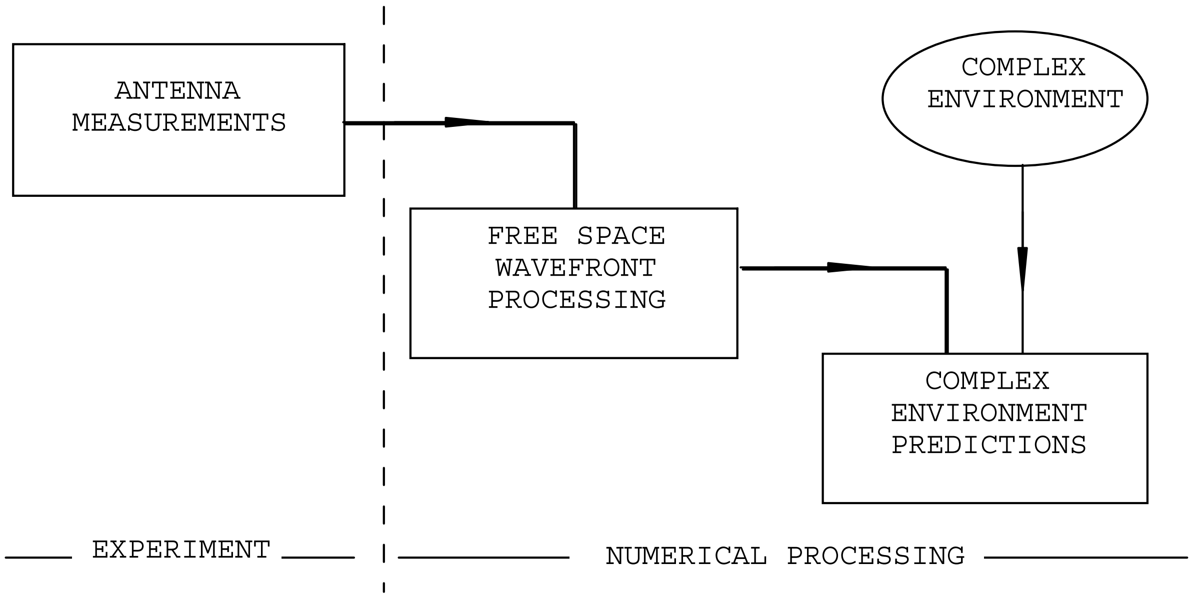
- APPLY TO TRUE EQUIPMENT
- NEEDS PROBE, RECEIVER, ENVIRONMENT...
  FOR MEASURING FIELD DISTRIBUTION, POWER, IMPEDANCE, ETC.
- RESULTING LIMITATIONS IN ACCURACY,SPEED...
- REQUIRES ERROR COMPENSATION/CALIBRATION
- FLEXIBILITY IN INVESTIGATING REAL
  PARAMETERS NOT ACCESSIBLE VIA MODELING
- SUITABLE FOR VALIDATING CODES
- REQUIRED FOR FINAL, ROUTINE... TESTING

NEED FOR HYBRID TECHNIQUES COMBINING ADVANTAGES OF NUMERICAL AND EXPERIMENTAL APPROACHES

OPTIMIZATION OF THE CHARACTERIZATION PROCESS

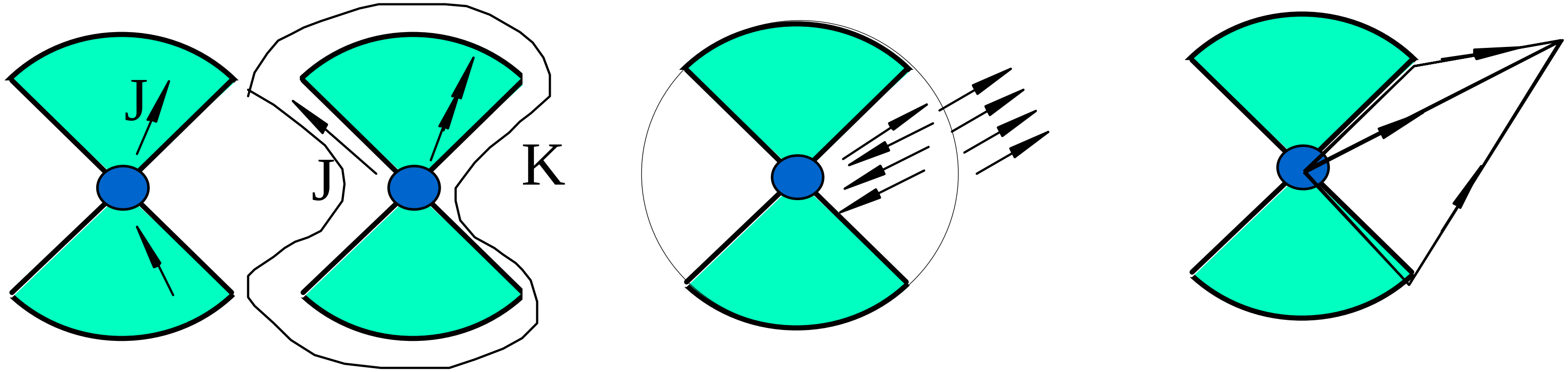
- **OPTIMIZATION PARAMETERS:**
  ACCURACY, RAPIDITY, FLEXIBILITY, COST, ETC.

- **COMBINING ADVANTAGES EXPERIMENTS AND NUMERICAL PROCESSING:**
  - MINIMIZING THE DATA ACQUISITION STEP ON TRUE EQUIPMENT
  - MAXIMIZING THE DATA PROCESSING STEP, TAKING PROFIT OF COMPUTER FLEXIBILITY



INTRODUCTION TO ANTENNA CHARACTERIZATION
SEVERAL WAYS
FOR CHARACTERIZING THE RADIATED FIELD

TRUE CURRENTS (ELECTRIC) | **EQUIVALENT CURRENTS** (ELECTRIC+MAGNETIC) | **MODES** | **RAYS**



CURRENT INTEGRATION

- INTEGRAL FORM FOR E AND H
- ARBITRARY SHAPE
- IMPLICIT DEPENDENCE E vs H
- CURRENTS DEDUCED FROM EFIE OR MFIE VIA MOMENT METHODS

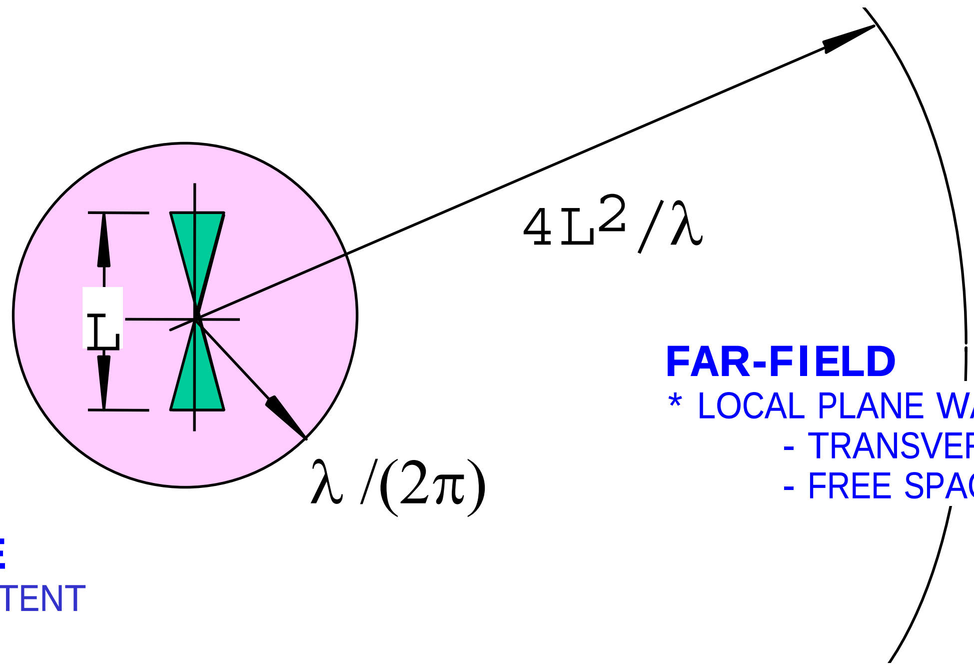
MODAL EXPANSION

- LIMITED NUMBER OF EFFECTIVE MODES
- ONLY SIMPLE SHAPES
- EXPLICIT DEPENDENCE E vs H
- MODE COEFFICIENTS DEDUCED FROM MODE MATCHING TECHNIQUES

RAY SUMMATION

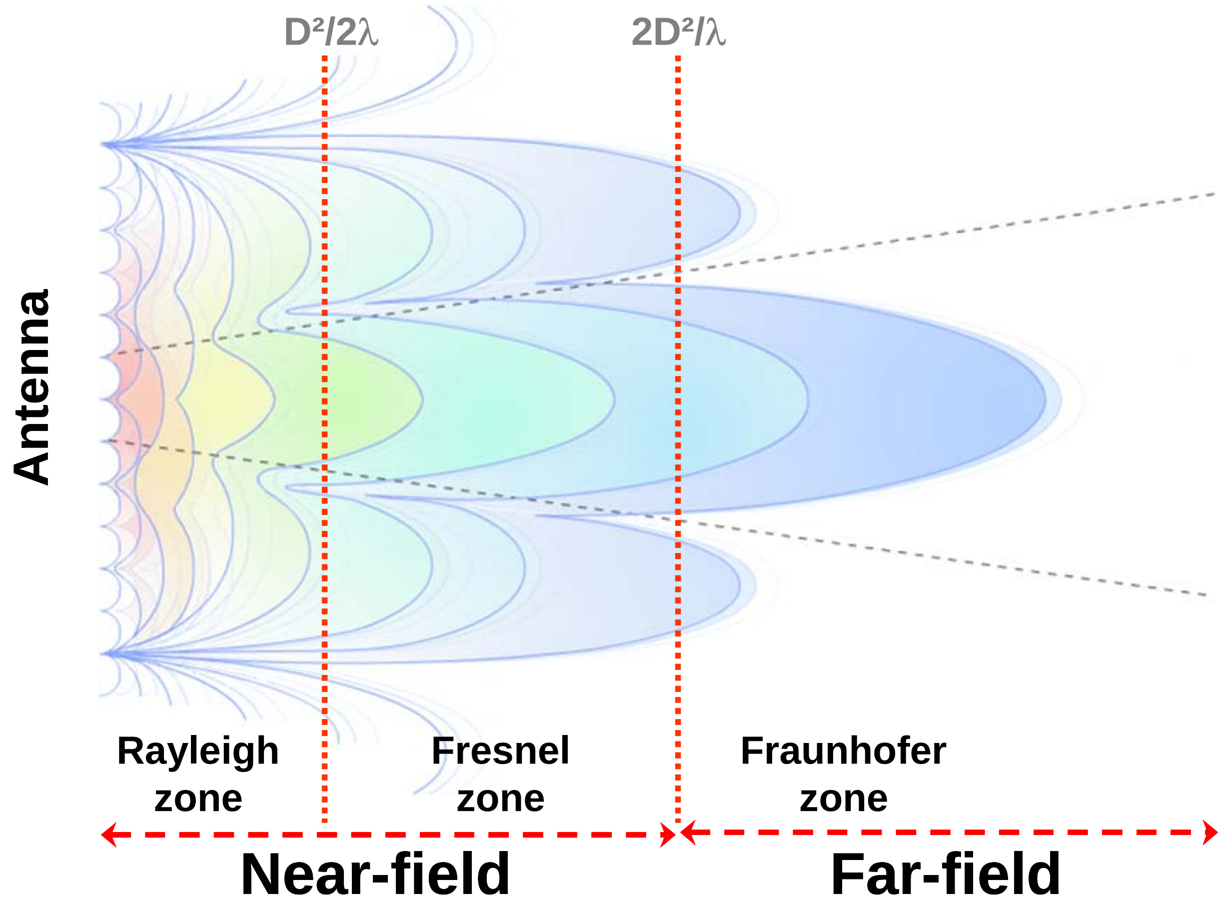
- LIMITED NUMBER OF EFFECTIVE RAYS
- ONLY ASYMPTOTICS l->0
- EXPLICIT DEPENDENCE E vs H
- RAYS DEDUCED FROM REFLEXION AND DIFFRACTION COEFFICIENTS

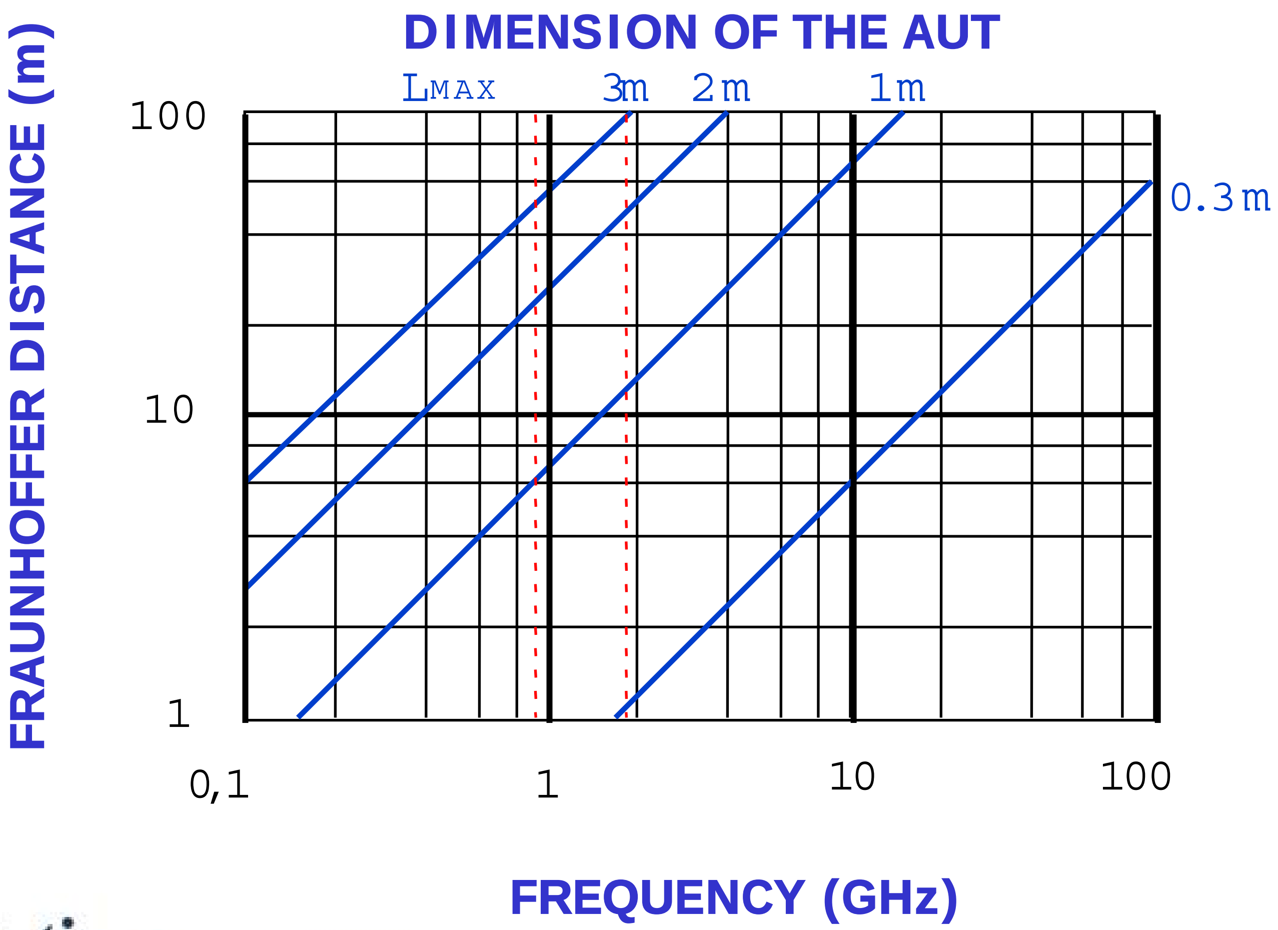
THE TRANSMITTING MODE
THE CASE OF ELECTRICALLY SMALL ANTENNAS
$L < \lambda$



FAR-FIELD
* LOCAL PLANE WAVE
  - TRANSVERSE EM FIELD
  - FREE SPACE IMPEDANCE

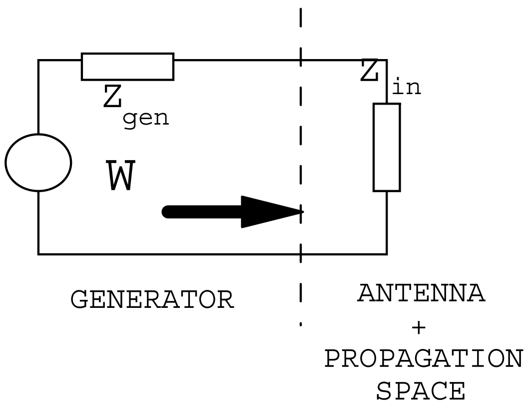
REACTIVE ZONE
* EVANESCENT CONTENT (QUASI-STATIC)
* REACTIVE POWER
* RADIAL COMPONENTS
* NON-FREE SPACE IMPEDANCE


D²/2λ
2D²/λ
Antenna
Rayleigh zone
Fresnel zone
Fraunhofer zone
Near-field
Far-field

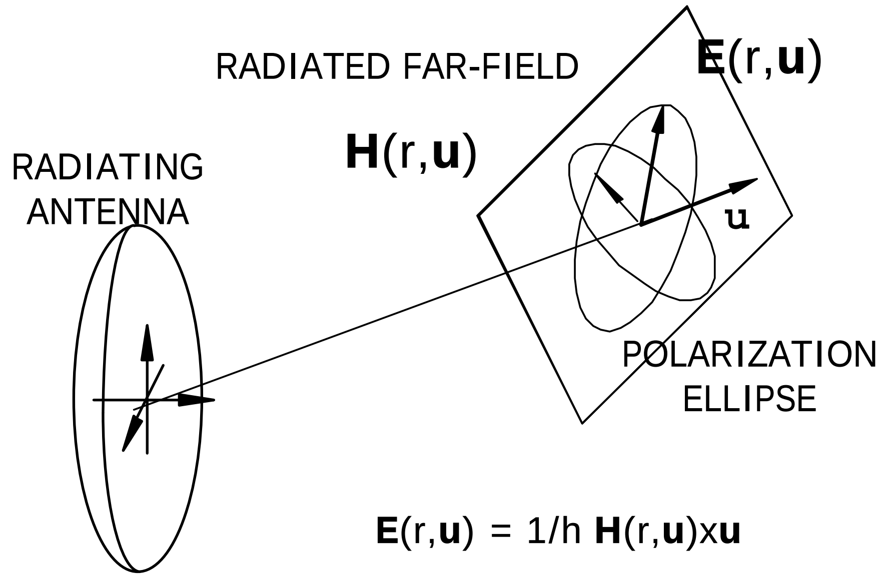


DIMENSION OF THE AUT
LMAX
3m
2m
1m
0.3m
100
10
1
0,1
1
10
100
FRAUNHOFFER DISTANCE (m)
FREQUENCY (GHz)

EQUIVALENT SCHEME



RADIATED FAR-FIELD



$$\mathbf{E}(r,\mathbf{u}) = 1/h\ \mathbf{H}(r,\mathbf{u}) \times \mathbf{u}$$

$$\mathbf{E}(r,\mathbf{u}) = \frac{e^{-jkr}}{r}\mathbf{F}(\mathbf{u})$$

Z_{in} INPUT IMPEDANCE

F(**u**) VECTOR RADIATION CHARACTERISTIC (SAF)

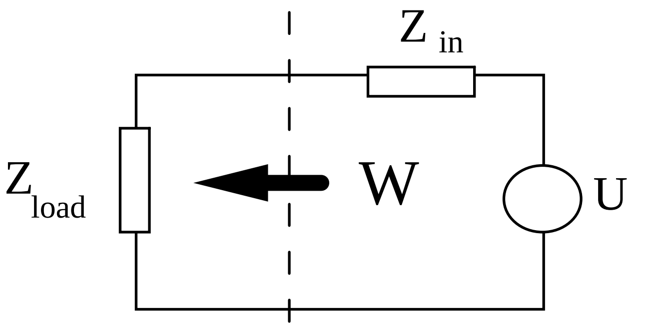
FAR-FIELD QUANTITIES OF PRACTICAL RELEVANCE

• $\mathbf{F}(\mathbf{u}) := \lim_{r \to \infty} \{ r\, e^{jkr}\, \mathbf{E}(r, \mathbf{u}) \}$	radiation vector characteristic in direction **u** (V/m) (Spherical Angular Function)
• $\sigma(\mathbf{u}) = F'^2/2\eta$	radiated power density per unit solid angle in direction **u** (W/std)
• $W_r = \iint_{4\pi} \sigma(\mathbf{u})\, d\Omega(\mathbf{u})$	total radiated power (W)
• W_a	applied active power (W)
• $W_r = \eta\, W_a$	η: radiation efficiency
• $D(\mathbf{u}) = 4\pi\, \sigma(\mathbf{u})/W_r$	directivity
• $G(\mathbf{u}) = 4\pi\, \sigma(\mathbf{u})/W_a$	gain $\quad G(\mathbf{u}) = \eta\, D(\mathbf{u})$

$$\iint_{4\pi} G(\mathbf{u})\, d\Omega(\mathbf{u}) = 4\pi\eta$$

THE RECEIVING MODE
ANTENNA PLANE WAVE RESPONSE

EQUIVALENT SCHEME



EQUIVALENT LOAD (RECEIVER)

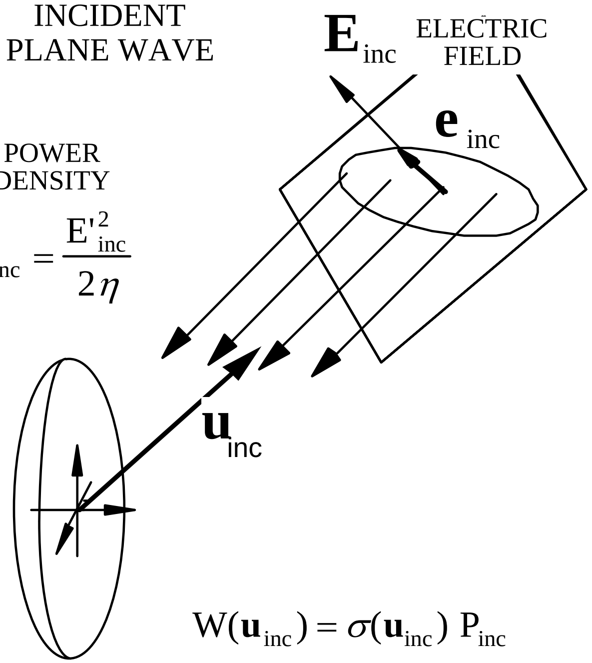
EQUIVALENT GENERATOR (ANTENNA + INCIDENT WAVE)

$$U = \frac{4\pi}{j\eta k}\mathbf{E}_{inc}.\mathbf{F}(\mathbf{u}_{inc})$$

INCIDENT PLANE WAVE

POWER DENSITY

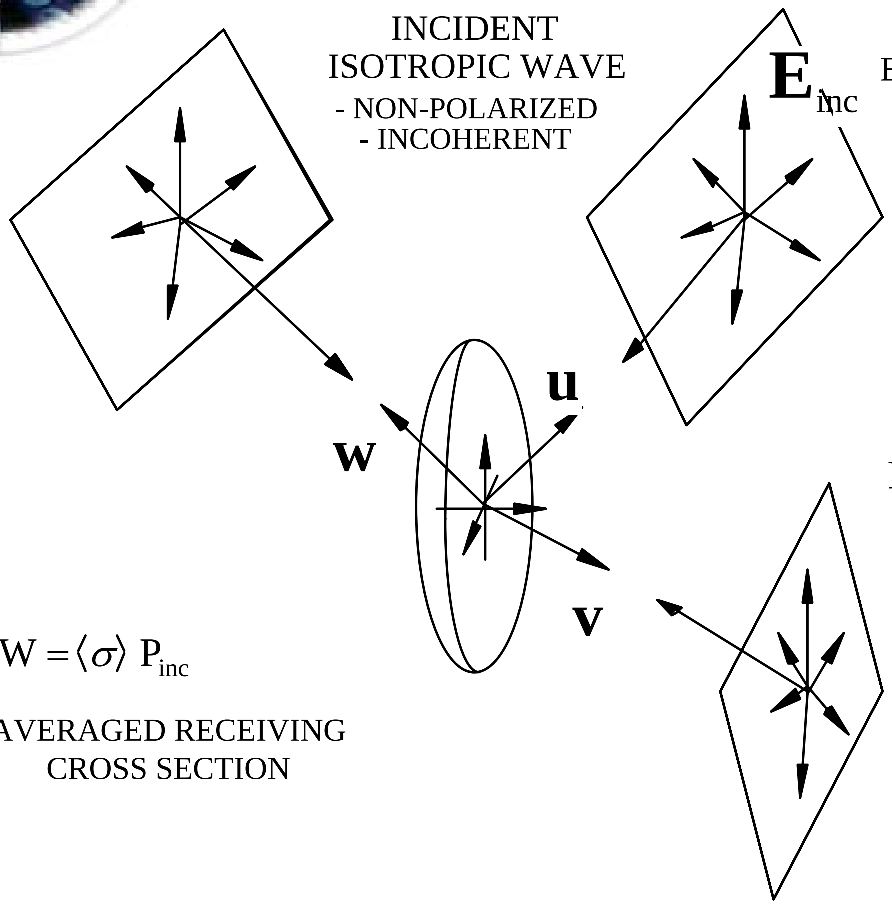
$$P_{inc} = \frac{E'^{2}_{inc}}{2\eta}$$



$$W(\mathbf{u}_{inc}) = \sigma(\mathbf{u}_{inc})\ P_{inc}$$

RECEIVING CROSS SECTION

THE RECEIVING MODE
ANTENNA ISOTROPIC WAVE RESPONSE



ELECTRIC FIELD

$$\langle E_x \rangle = \langle E_y \rangle = \langle E_z \rangle = 0$$

$$\langle E_x^2 \rangle = \langle E_y^2 \rangle = \langle E_z^2 \rangle = 1/3 \; E_0^2$$

POWER DENSITY

$$P_{inc} = \frac{E'^2_0}{2\eta}$$

$$W = \langle \sigma \rangle \, P_{inc}$$

AVERAGED RECEIVING CROSS SECTION

PLANE WAVE ANALYSIS

$W(\mathbf{u}) = \sigma(\mathbf{u})\ P_{inc}$

$\sigma(\mathbf{u}) = \lambda^2/4\pi\ \rho_{load}\ \rho_{pol}(\mathbf{u})\ G(\mathbf{u})$

coupling cross section

$\rho_{load} = 1 - \left| \dfrac{Z_{in} - Z^*_{load}}{Z_{in} + Z_{load}} \right|^2$ load factor

$\rho_{pol}(\mathbf{u}) = \left| \mathbf{e}_{inc} . \mathbf{f}(\mathbf{u}) \right|^2$ polarization factor

$G(\mathbf{u})$ gain

⇔

INTEGRATION OVER INCIDENCE ANGLE & POLARIZATION

ISOTROPIC WAVE ANALYSIS

$W = < \sigma > P_{inc,eq}$

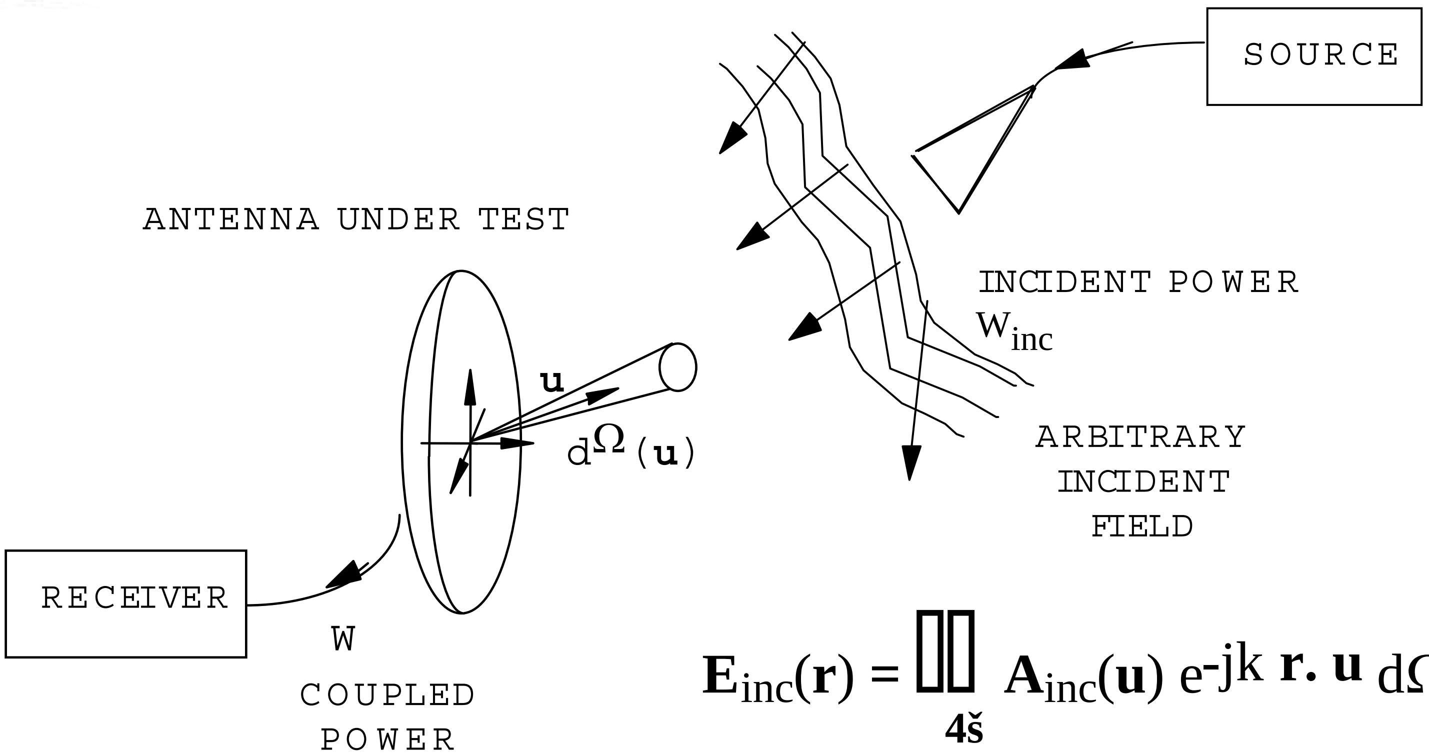
$< \sigma > = \lambda^2/2\ \rho_{load}$

* time non-coherent fields:
  ⇒ power summation
* isotropic fields:
  ⇒ angular integration

  $\iint G(\mathbf{u})\ d\Omega(\mathbf{u}) = 4\pi$

* non-polarized fields:
  ⇒ $\rho_{pol}(\mathbf{u}) = \mathbf{1/2}$

THE RECEIVING MODE
ANTENNA ISOTROPIC WAVE RESPONSE



$$\mathbf{E}_{inc}(\mathbf{r}) = \iint_{4\pi} \mathbf{A}_{inc}(\mathbf{u})\, e^{-jk\,\mathbf{r}.\,\mathbf{u}}\, d\Omega(\mathbf{u})$$

SUPERPOSITION OF PLANE WAVES

COUPLED POWER $$W(\mathbf{u}) = \rho_{load}\,\overline{\rho_{pol}}\,W_{inc}$$

load factor

$$\rho_{load} = 1 - \left| \frac{Z_{in} - Z^*_{load}}{Z_{in} + Z_{load}} \right|^2$$

polarization / coupling factor

$$\overline{\rho_{pol}}(\mathbf{u}) = \frac{\left| < \mathbf{A}_{inc}, \ \mathbf{F}^* > \right|^2}{\left\| \mathbf{A}_{inc} \right\|^2 \ \left\| \mathbf{F} \right\|^2}$$

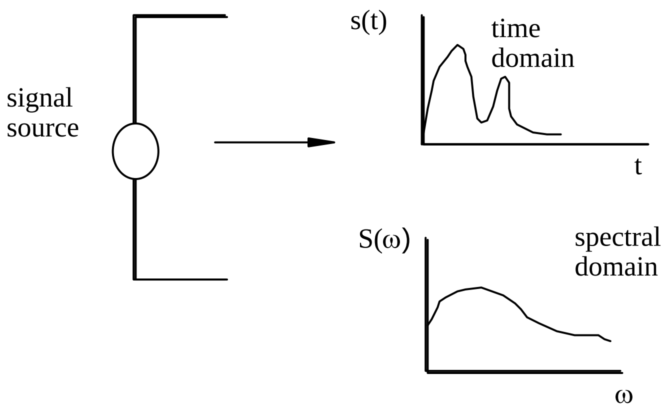
scalar product, norm

$$< \mathbf{U} \, , \mathbf{V} > = \iint_{4\pi} \mathrm{U}(\mathbf{u}) \, . \, \mathbf{V}^*(\mathbf{u}) \, d\Omega(\mathbf{u})$$

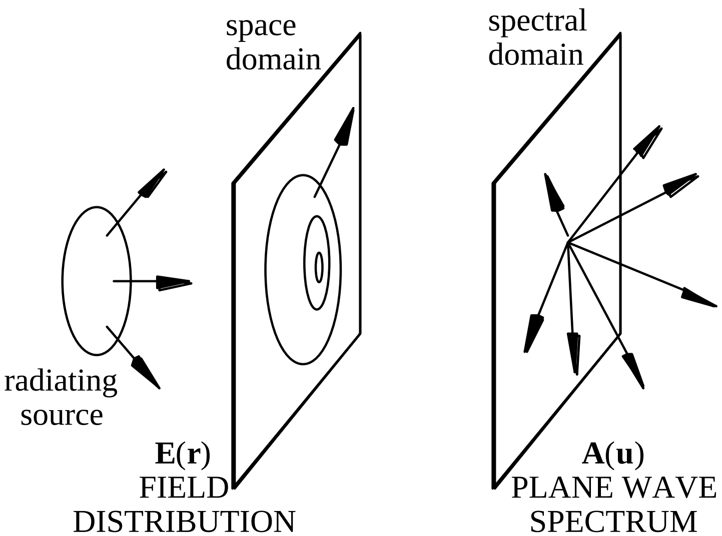
$$\left\| \mathbf{U} \right\|^2 = < \mathbf{U} \, , \mathbf{U} > = \mathrm{U}'^2$$

CORRESPONDENCE BETWEEN SIGNALS AND WAVES (1)

SIGNALS



WAVES



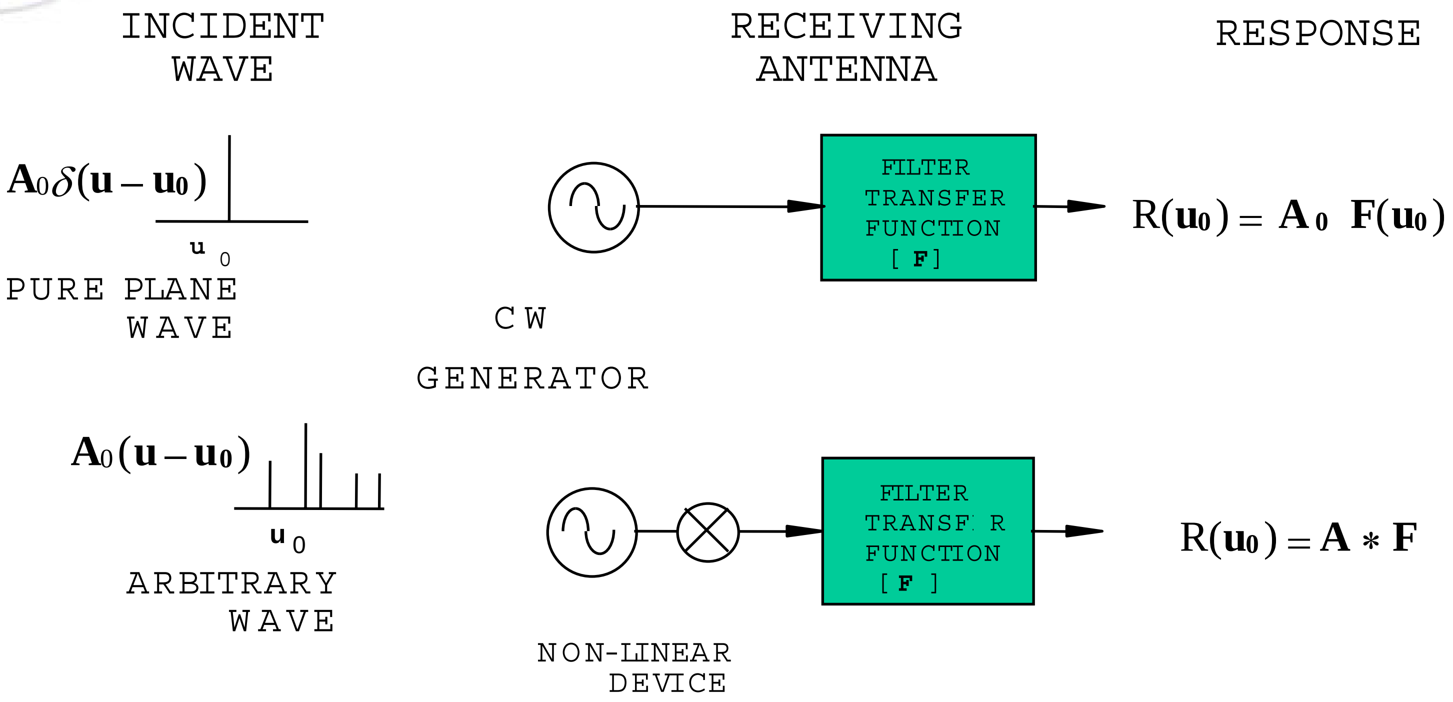
$$\Phi(\mathbf{r},t)= \omega t - \mathbf{k}.\mathbf{r}$$

THE ANTENNA AS A LINEAR FILTER
CORRESPONDENCE BETWEEN SIGNALS AND WAVES (2)

FOURIER TRANSFORM

SIGNALS (1D, SCALAR)	**WAVES** (2D, VECTOR)
TIME DOMAIN t TIME DEPENDENCE $s(t)$	SPACE DOMAIN $\mathbf{r} \in S$ SPATIAL DEPENDENCE $\mathbf{E}(\mathbf{r})$
ANGULAR FREQUENCY DOMAIN ω FREQUENCY SPECTRUM $S(\omega)$	SPATIAL FREQUENCY DOMAIN $\mathbf{k} = k\,\mathbf{u}$ PLANE WAVE SPECTRUM (SAF) $\mathbf{F}(\mathbf{u})$

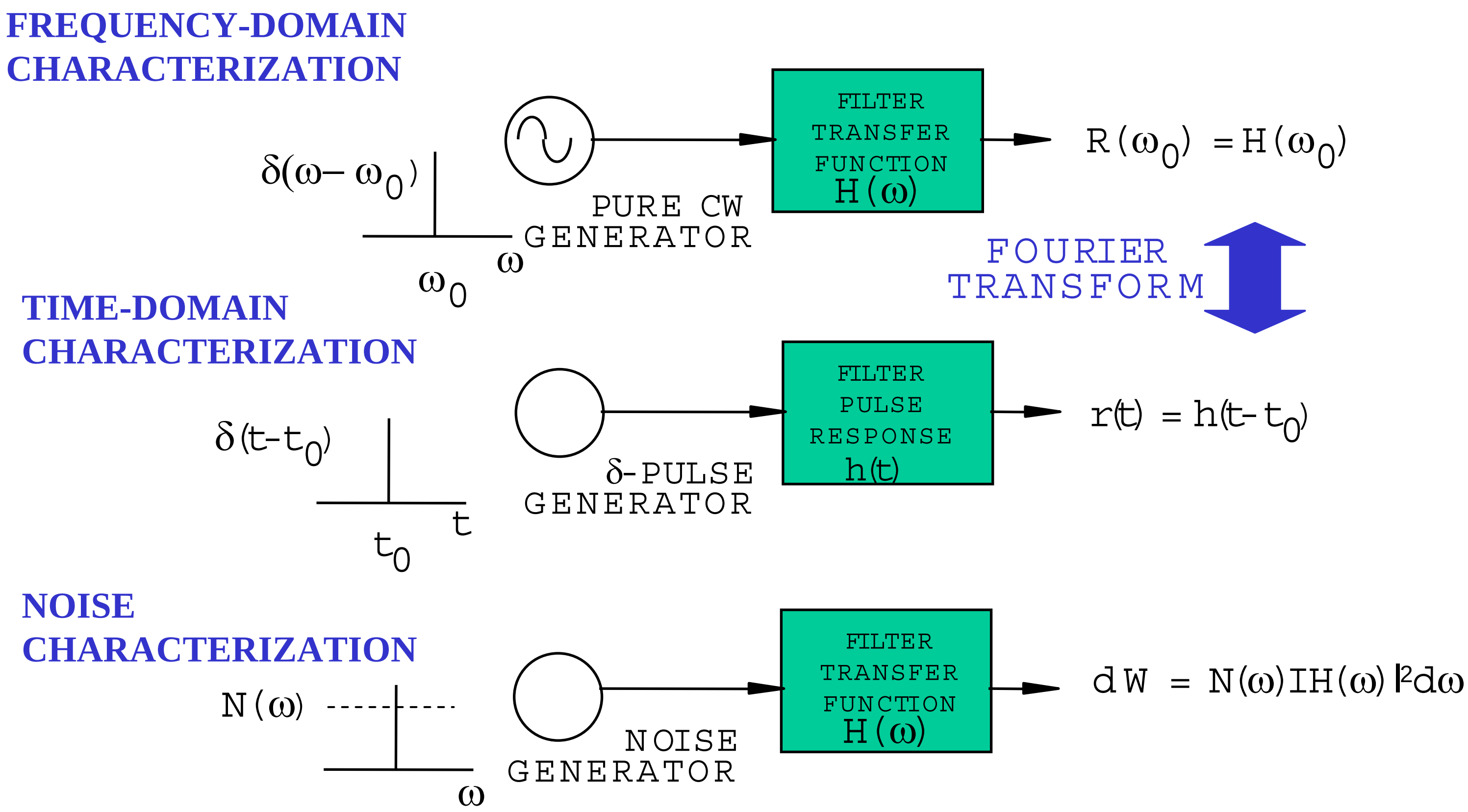
SIGNALS / WAVES EQUIVALENCE



2 PROBLEMS OF PRACTICAL RELEVANCE:

- ANTENNA CHARACTERIZATION: **A** IS KNOWN, DETERMINE **F**
- FIELD MEASUREMENT: **F** IS KNOWN, DETERMINE **A**

DIFFERENT CHARACTERIZATION TECHNIQUES FOR LINEAR COMPONENTS



CIRCUIT ANALOGY	METHODOLOGY FOR ANTENNA CHARACTERIZATION	
FREQUENCY-DOMAIN	PLANE WAVE TESTING	**DIRECT** MEASUREMENT OF FF PATTERNS IN LONG OR COMPACT RANGES
TIME-DOMAIN	NEAR-FIELD TECHNIQUE	**IN DIRECT** MEASUREMENT OF FF PATTERNS IN NEAR-FIELD FACILITIES
WHITE NOISE	ISOTROPIC WAVE TESTING	MEASUREMENT OF THE TOTAL RADIATED POWER IN REVERBERATING CHAMBERS

CONCLUSION

- FAR FIELD ANTENNA RADIATION IS WELL DEPICTED BY THE VECTOR RADIATION CHARACTERISTICS

- ANY INCIDENT FIELD CAN BE EXPANDED AS A SUPERPOSITION OF PLANE WAVES (PLANE WAVE SPECTRUM)

- ANTENNA RESPONSE, IN ARBITRARY INCIDENT FIELD, CAN BE DEDUCED FROM ITS PLANE WAVE RESPONSE

- WAVES / SIGNALS ANALOGY:
  - LEADS TO CONSIDER AN ANTENNA AS A LINEAR ANGULAR FILTER
  - PROVIDES A VALUABLE SUPPORT TO UNDERSTANDING AND COMPARE DIFFERENT ANTENNA MEASUREMENT TECHNIQUES

射 频 和 天 线 设 计 培 训 课 程 推 荐

易迪拓培训(www.edatop.com)由数名来自于研发第一线的资深工程师发起成立，致力并专注于微波、射频、天线设计研发人才的培养；我们于 2006 年整合合并微波 EDA 网(www.mweda.com)，现已发展成为国内最大的微波射频和天线设计人才培养基地，成功推出多套微波射频以及天线设计经典培训课程和 ADS、HFSS 等专业软件使用培训课程，广受客户好评；并先后与人民邮电出版社、电子工业出版社合作出版了多本专业图书，帮助数万名工程师提升了专业技术能力。客户遍布中兴通讯、研通高频、埃威航电、国人通信等多家国内知名公司，以及台湾工业技术研究院、永业科技、全一电子等多家台湾地区企业。

易迪拓培训推荐课程列表： http://www.edatop.com/peixun/tuijian/

射频工程师养成培训课程套装

该套装精选了射频专业基础培训课程、射频仿真设计培训课程和射频电路测量培训课程三个类别共 30 门视频培训课程和 3 本图书教材；旨在引领学员全面学习一个射频工程师需要熟悉、理解和掌握的专业知识和研发设计能力。通过套装的学习，能够让学员完全达到和胜任一个合格的射频工程师的要求…

课程网址：http://www.edatop.com/peixun/rfe/110.html

手机天线设计培训视频课程

该套课程全面讲授了当前手机天线相关设计技术，内容涵盖了早期的外置螺旋手机天线设计，最常用的几种手机内置天线类型——如 monopole 天线、PIFA 天线、Loop 天线和 FICA 天线的设计，以及当前高端智能手机中较常用的金属边框和全金属外壳手机天线的设计；通过该套课程的学习，可以帮助您快速、全面、系统地学习、了解和掌握各种类型的手机天线设计，以及天线及其匹配电路的设计和调试...

课程网址： http://www.edatop.com/peixun/antenna/133.html

WiFi 和蓝牙天线设计培训课程

该套课程是李明洋老师应邀给惠普 (HP)公司工程师讲授的 3 天员工内训课程录像，课程内容是李明洋老师十多年工作经验积累和总结，主要讲解了 WiFi 天线设计、HFSS 天线设计软件的使用，匹配电路设计调试、矢量网络分析仪的使用操作、WiFi 射频电路和 PCB Layout 知识，以及 EMC 问题的分析解决思路等内容。对于正在从事射频设计和天线设计领域工作的您，绝对值得拥有和学习！…

课程网址：http://www.edatop.com/peixun/antenna/134.html

CST 学习培训课程套装

该培训套装由易迪拓培训联合微波 EDA 网共同推出，是最全面、系统、专业的 CST 微波工作室培训课程套装，所有课程都由经验丰富的专家授课，视频教学，可以帮助您从零开始，全面系统地学习 CST 微波工作的各项功能及其在微波射频、天线设计等领域的设计应用。且购买该套装，还可超值赠送 3 个月免费学习答疑…

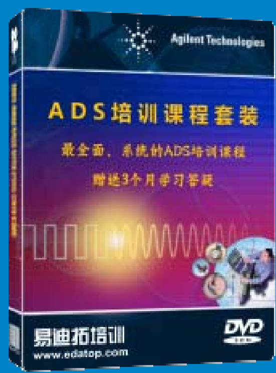
课程网址：http://www.edatop.com/peixun/cst/24.html

HFSS 学习培训课程套装

该套课程套装包含了本站全部 HFSS 培训课程，是迄今国内最全面、最专业的 HFSS 培训教程套装，可以帮助您从零开始，全面深入学习 HFSS 的各项功能和在多个方面的工程应用。购买套装，更可超值赠送 3 个月免费学习答疑，随时解答您学习过程中遇到的棘手问题，让您的 HFSS 学习更加轻松顺畅…

课程网址：http://www.edatop.com/peixun/hfss/11.html

ADS 学习培训课程套装



该套装是迄今国内最全面、最权威的 ADS 培训教程，共包含 10 门 ADS 学习培训课程。课程是由具有多年 ADS 使用经验的微波射频与通信系统设计领域资深专家讲解，并多结合设计实例，由浅入深、详细而又全面地讲解了 ADS 在微波射频电路设计、通信系统设计和电磁仿真设计方面的内容。能让您在最短的时间内学会使用 ADS，迅速提升个人技术能力，把 ADS 真正应用到实际研发工作中去，成为 ADS 设计专家...

课程网址： http://www.edatop.com/peixun/ads/13.html

我们的课程优势：

※ 成立于 2004 年，10 多年丰富的行业经验，

※ 一直致力并专注于微波射频和天线设计工程师的培养，更了解该行业对人才的要求

※ 经验丰富的一线资深工程师讲授，结合实际工程案例，直观、实用、易学

联系我们：

※ 易迪拓培训官网：http://www.edatop.com

※ 微波 EDA 网：http://www.mweda.com

※ 官方淘宝店：http://shop36920890.taobao.com