UWB Double-Directional Channel Sounding

- Why and how? -

Jun-ichi Takada

Tokyo Institute of Technology, Japan

takada@ide.titech.ac.jp

Table of Contents

- Background
- Antennas and propagation in UWB
- Propagation issues relating with MIMO
- UWB double directional channel sounding
- Evaluation and modeling issues of sounding thechnology

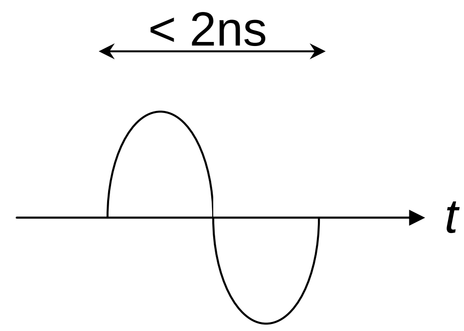
Ultra Wideband Radio

- FCC definition in US
  - 20% or 500MHz — *Spread spectrum*
  - 3.1GHz ~ 10.6GHz — *Avoid dense application*
  - -41.3dBm — *Coexistence*

Trend of UWB – IEEE 802.15.3a

Impulse radio

- Simple hardware
- Low power consumption

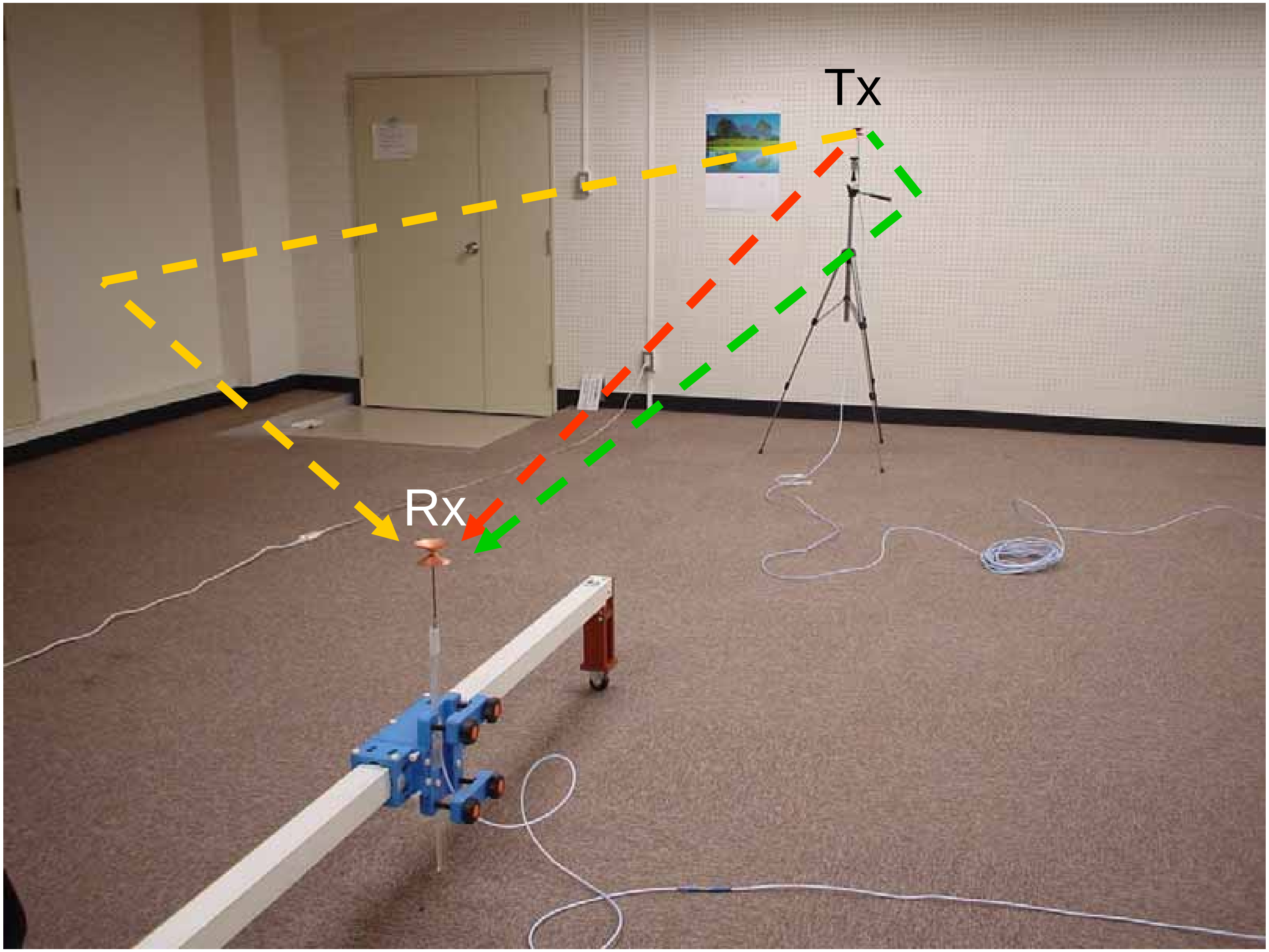


IEEE 802.15 TG3a : High Speed Personal Area Network

DS-CDMA

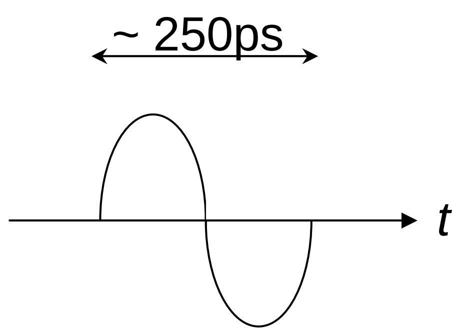
MB-OFDM

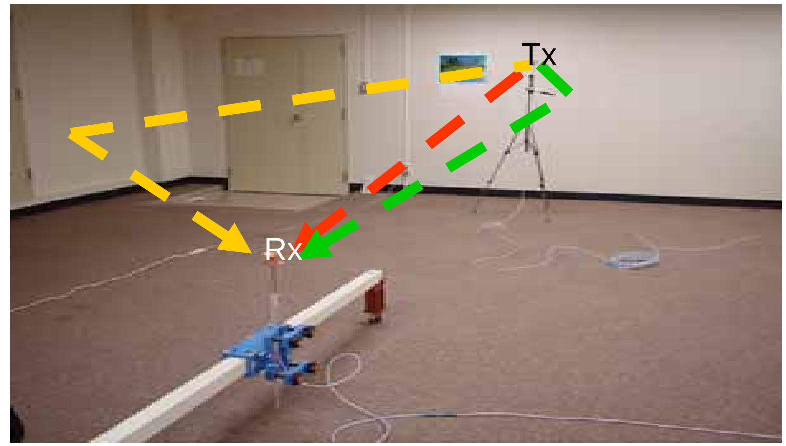
Indoor Multipath Environment



Transmission in Multipath Environment

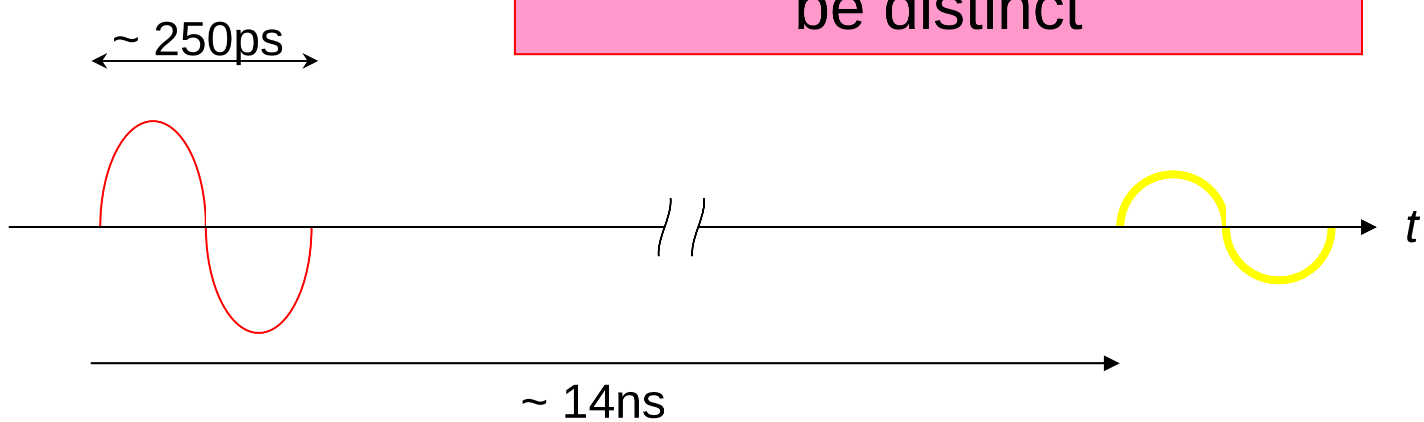
Tx pulse (4GHz BW)



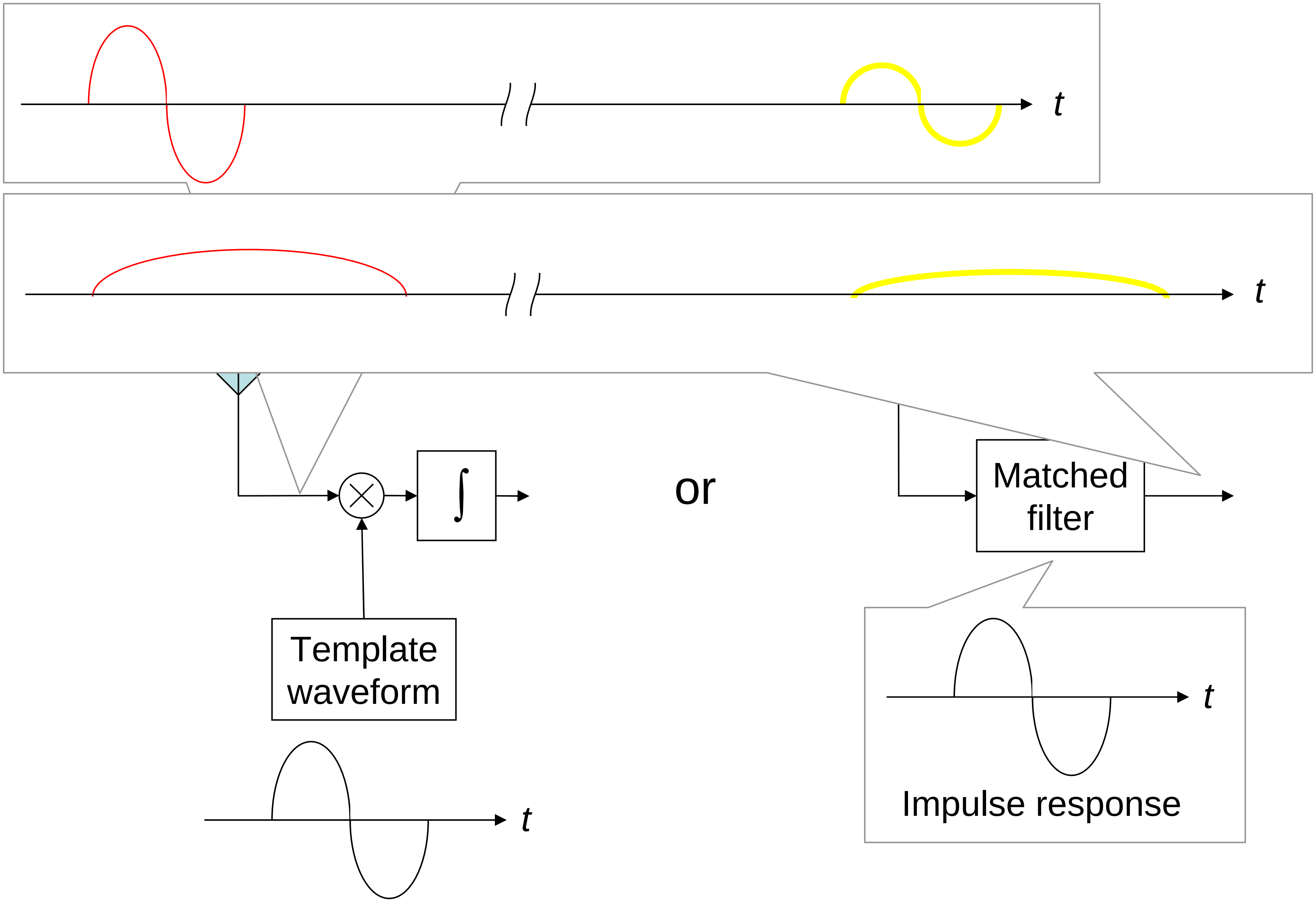


Rx pulse

Multipath components can be distinct

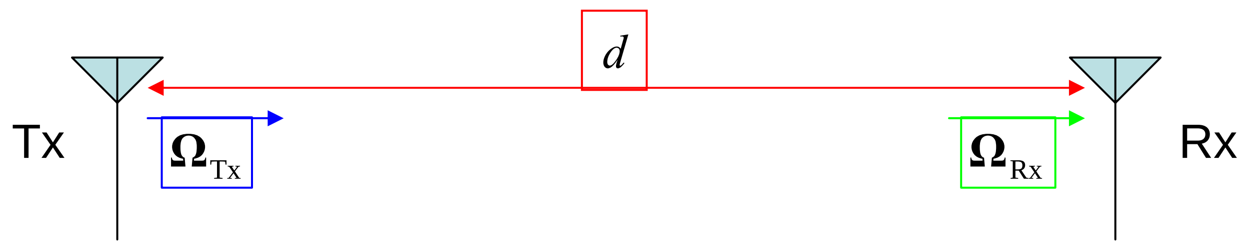


UWB Receiver



Free Space Transfer Function

- Friis' transmission formula



$$H_{\mathrm{Friis}}(f) = H_{\mathrm{Free\,Space}}(f,d)\,\mathbf{H}_{\mathrm{Tx}}(f,\mathbf{\Omega}_{\mathrm{Tx}})\cdot\mathbf{H}_{\mathrm{Rx}}(f,\mathbf{\Omega}_{\mathrm{Rx}})$$

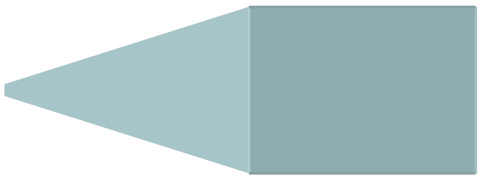
$$\propto \frac{1}{f}$$

Normalized by isotropic antenna

Ideal Antenna Cases

- Constant aperture size

Example : Pyramidal horn

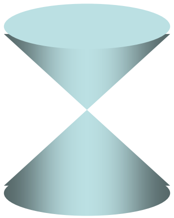


$$H_{\text{Ant}} \dot{\propto} f$$

$$\Rightarrow \quad H_{\text{Friis}} \dot{\propto} f$$

- Constant gain

Example : Biconical



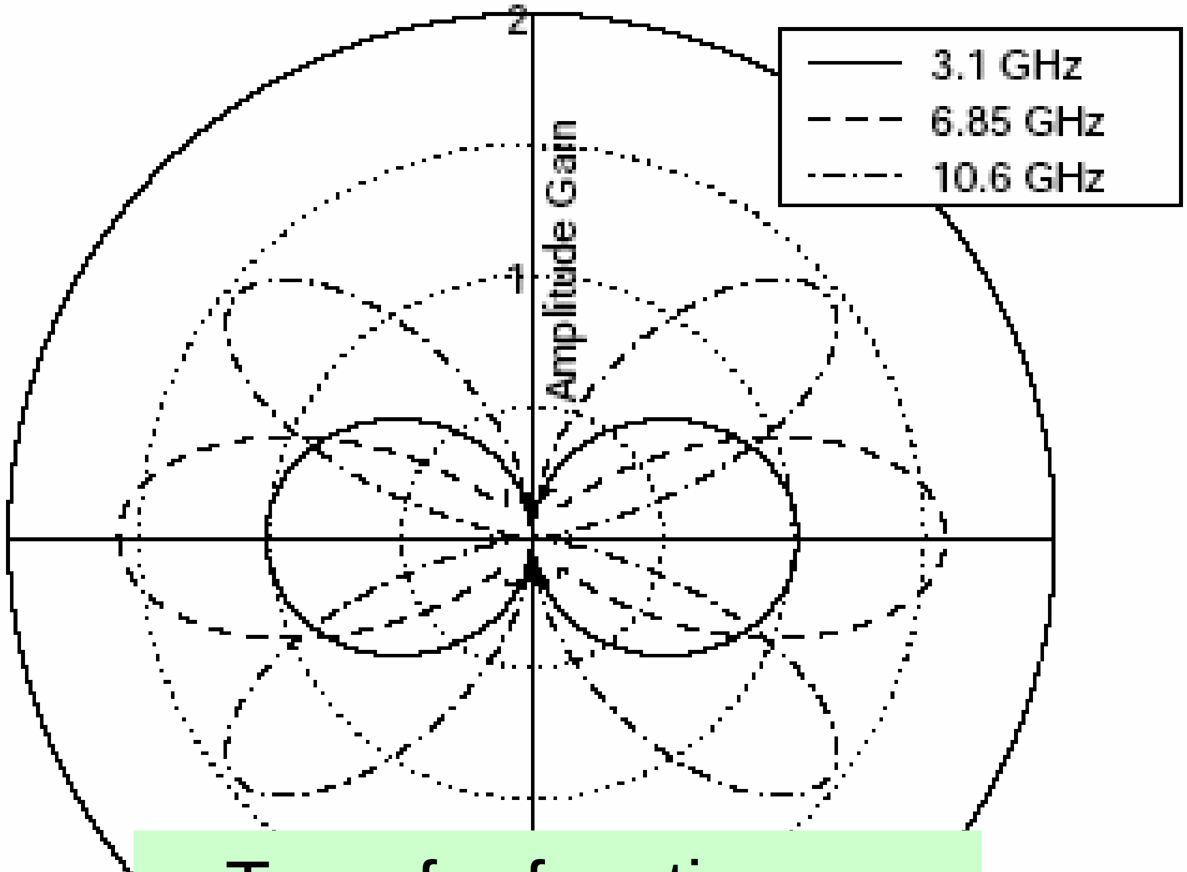
$$H_{\text{Ant}} \doteq \text{const.}$$

$$\Rightarrow \quad H_{\text{Friis}} \dot{\propto} \frac{1}{f}$$

Both are too idealized

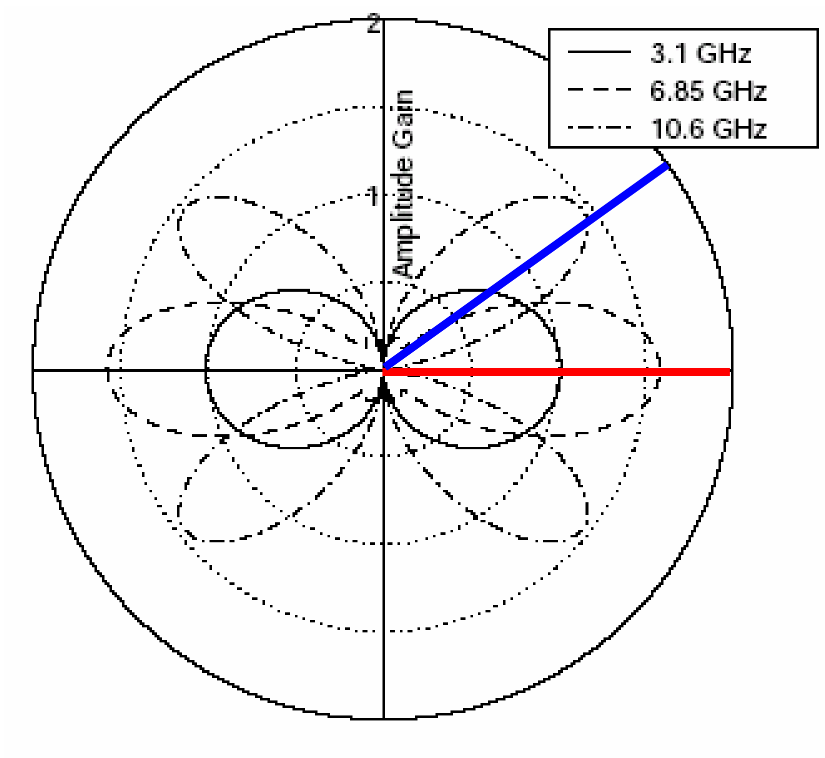
Frequency Characteristics of Antenna

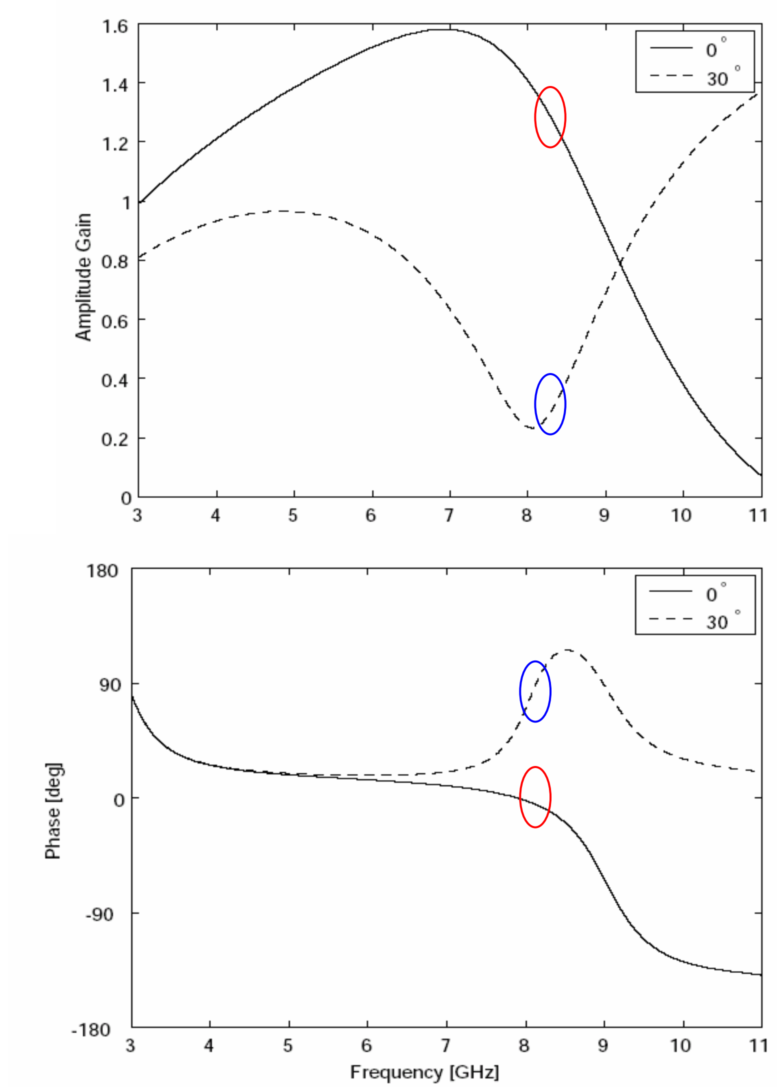
4.8cm Dipole (resonant at 3.1GHz)



- Transfer function
  - Frequency dependent
  - Angular dependent

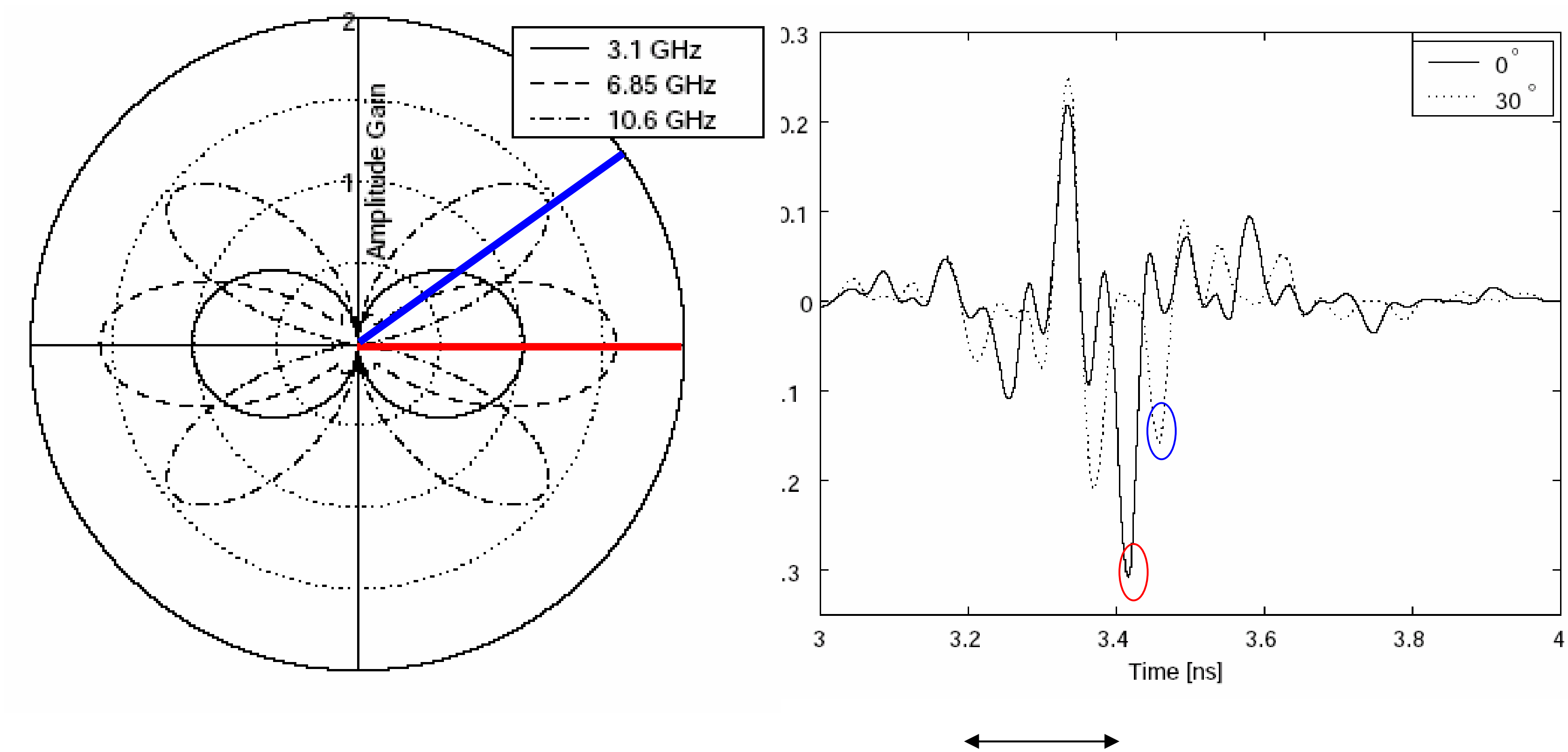
Directional Transfer Function of Antenna





Drastically changed by direction

Directional Impulse Response of Antenna



0.2ns

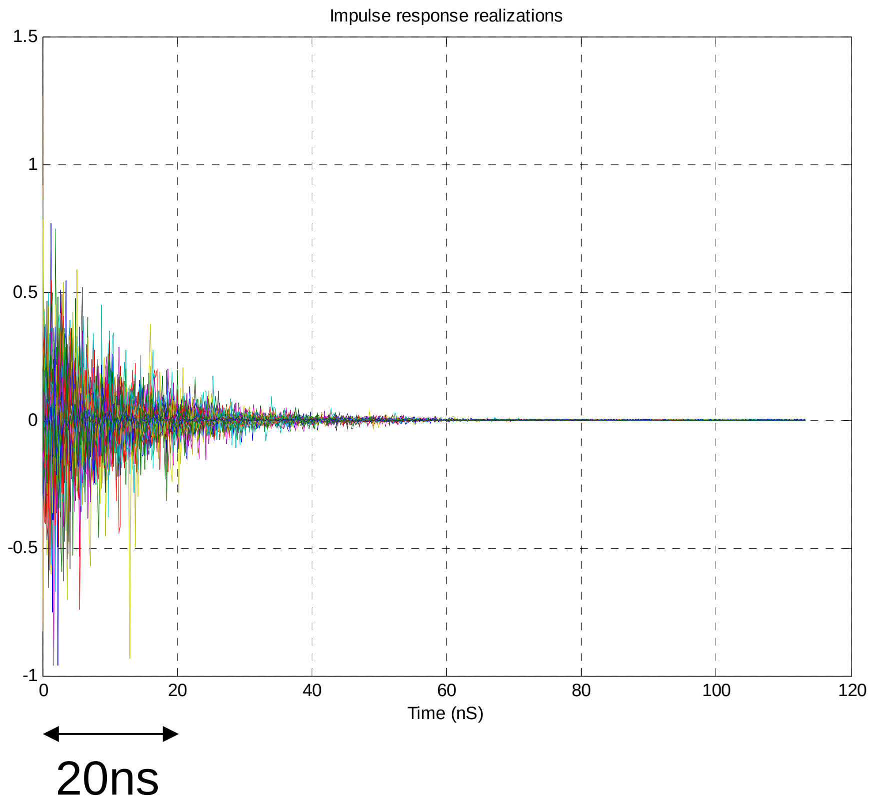
Conventional System vs UWB

Antenna and propagation issues

	Conventional systems	UWB-IR
Antenna	Gain (frequency flat)	Distortion
Multipath	Distortion	Distinction

Conventional Channel Model

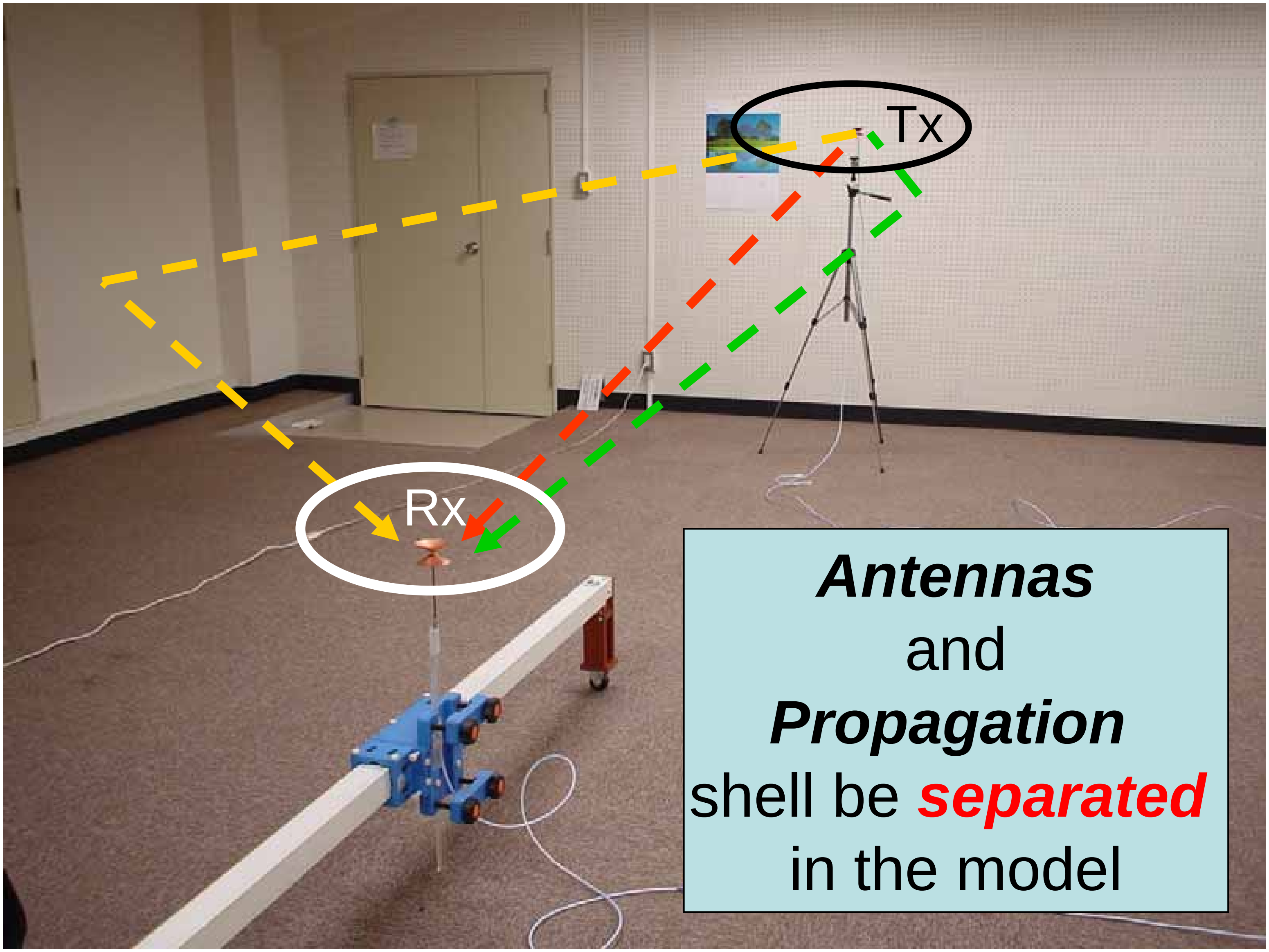
IEEE 802.15.3a Model



Channel includes antennas and propagation

Valid only for test antennas (omni) !

Channel Modeling Approach of UWB



Antennas
and
Propagation
shell be ***separated***
in the model

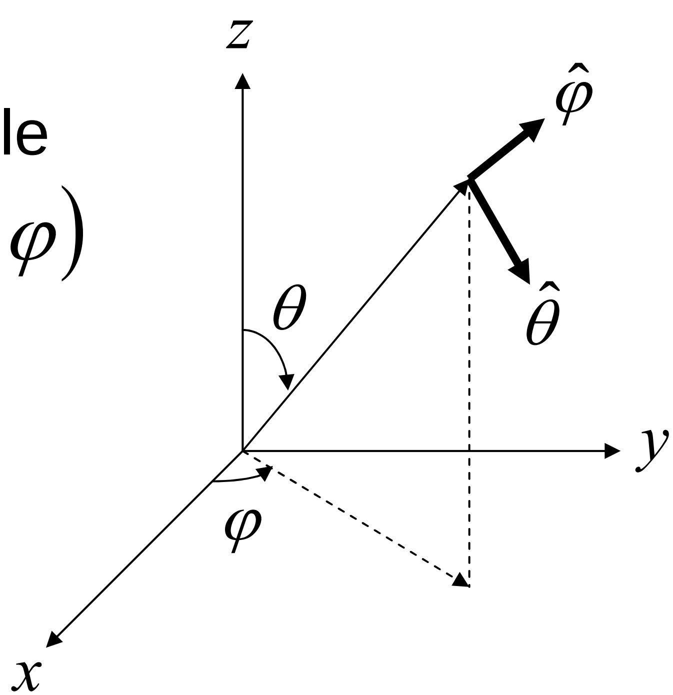
Antenna Model Parameters

Directive Polarimetric Frequency Transfer Function

$$\mathbf{H}_{\text{Ant}}(f,\theta,\varphi)=\hat{\boldsymbol{\theta}}(\theta,\varphi)H_{\theta,\text{Ant}}(f,\theta,\varphi)+\hat{\varphi}(\theta,\varphi)H_{\varphi,\text{Ant}}(f,\theta,\varphi)$$

Solid angle

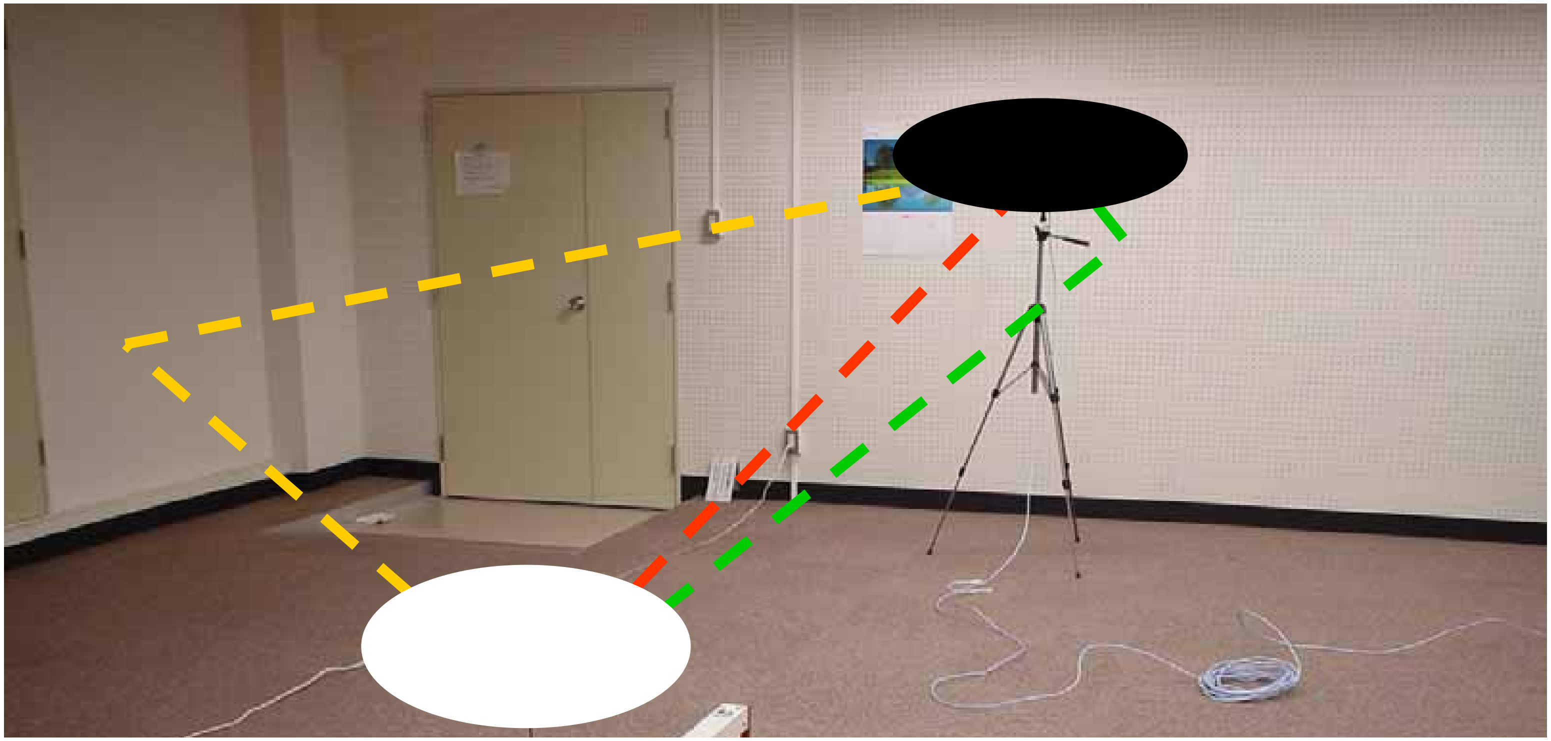
$$\mathbf{\Omega}=(\theta,\varphi)$$



How to Get Antenna Model Parameters

- Electromagnetic (EM) wave simulator
  - MoM (NEC, FEKO, …)
  - FEM (HFSS, …)
  - FDTD (XFDTD, …)
  - …
- Spherical polarimetric measurement
  - Three antenna method for testing antenna calibration

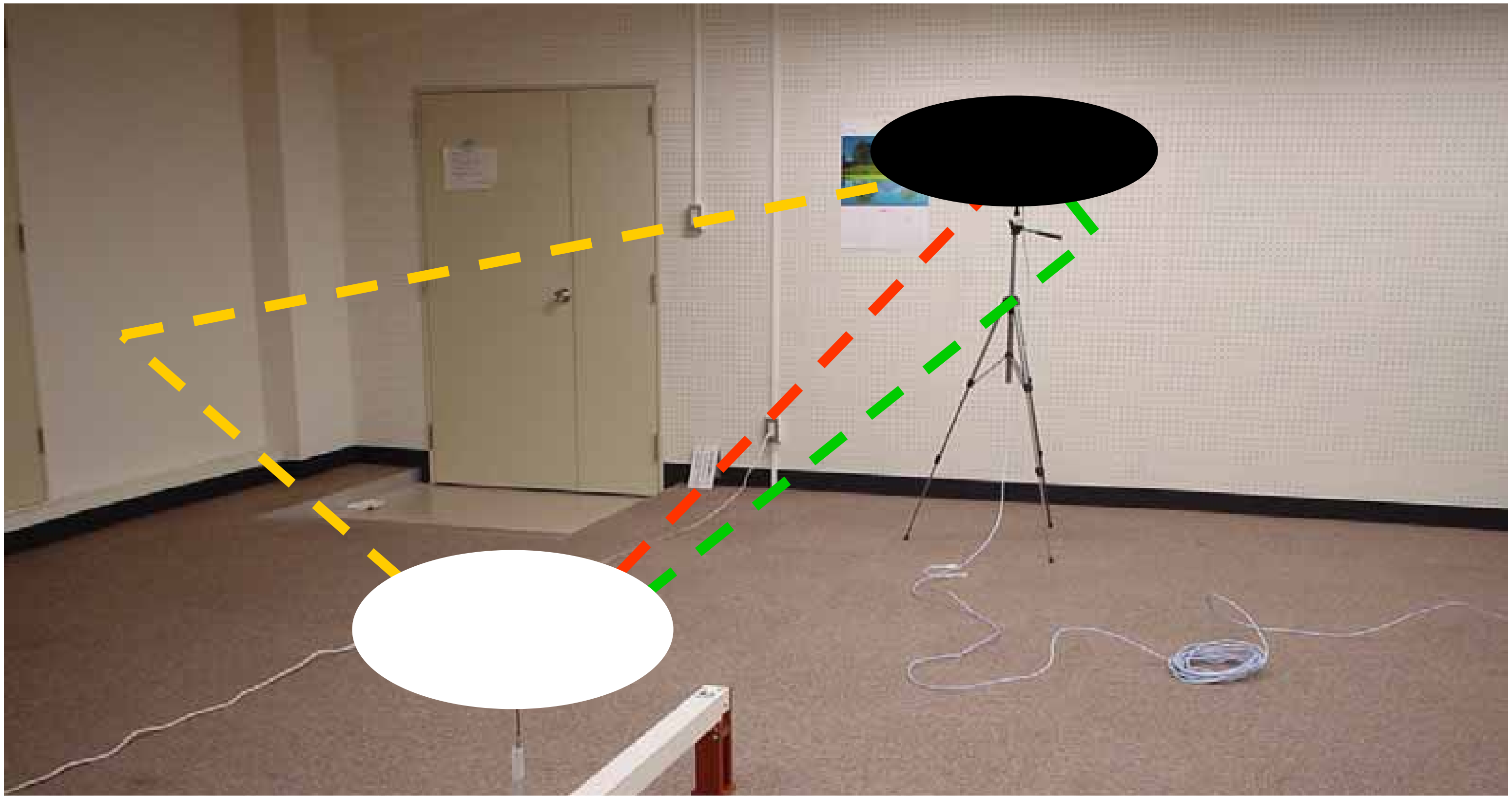
Propagation Modeling



Double-directional model

- Direction of departure (DoD)
- Direction of arrival (DoA)
- Delay time (DT)
- Magnitude (polarimetric, frequency dependent)

Double Directional Ray Model

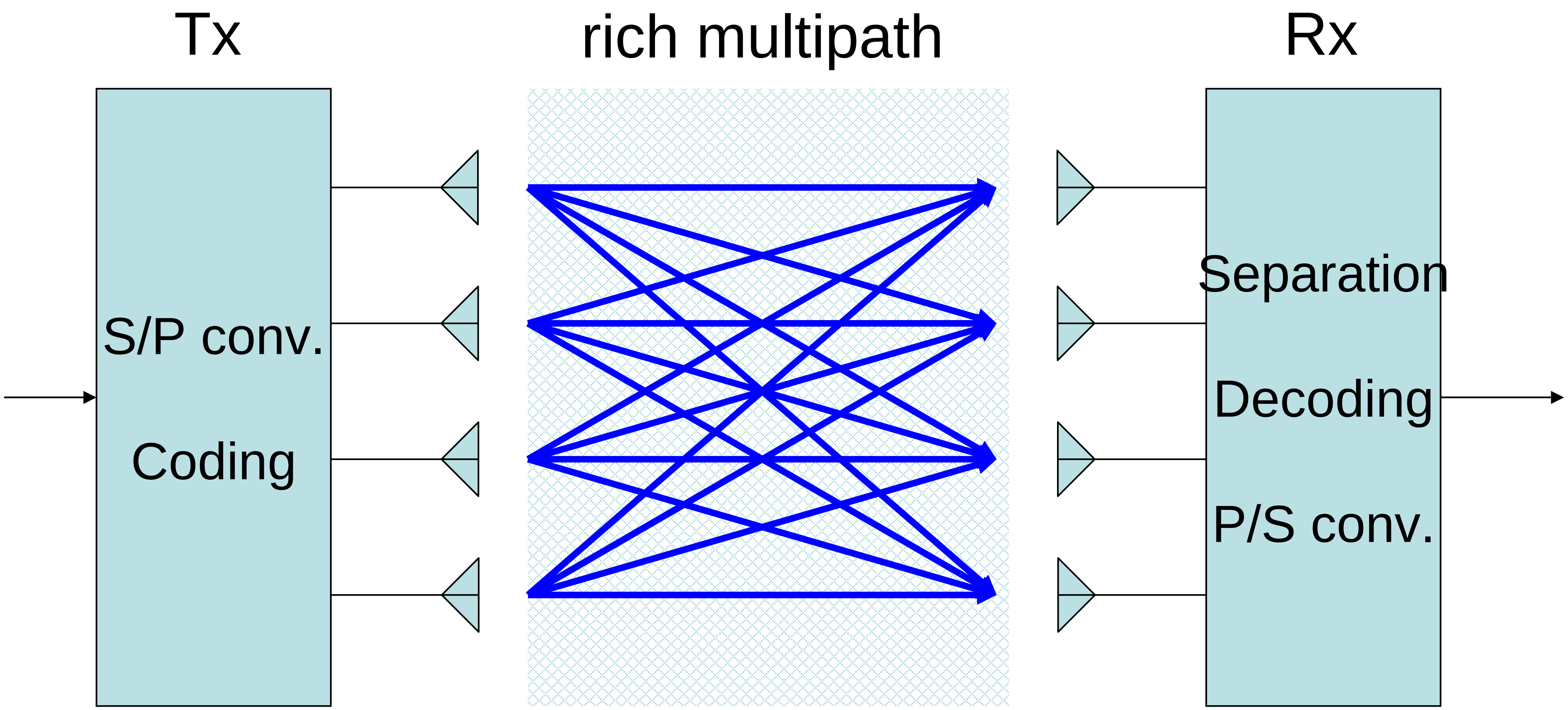


$$H_{\mathrm{Multipath}}\left(f,\mathbf{\Omega}_{\mathrm{Tx}},\mathbf{\Omega}_{\mathrm{Rx}}\right)=$$

$$\sum_{l=1}^{L} a_l(f)\,\delta\left(\mathbf{\Omega}_{\mathrm{Tx}}-\mathbf{\Omega}_{\mathrm{Tx},l}\right)\delta\left(\mathbf{\Omega}_{\mathrm{Rx}}-\mathbf{\Omega}_{\mathrm{Rx},l}\right)\exp\left(-\mathrm{j}\,2\pi f\tau_l\right)$$

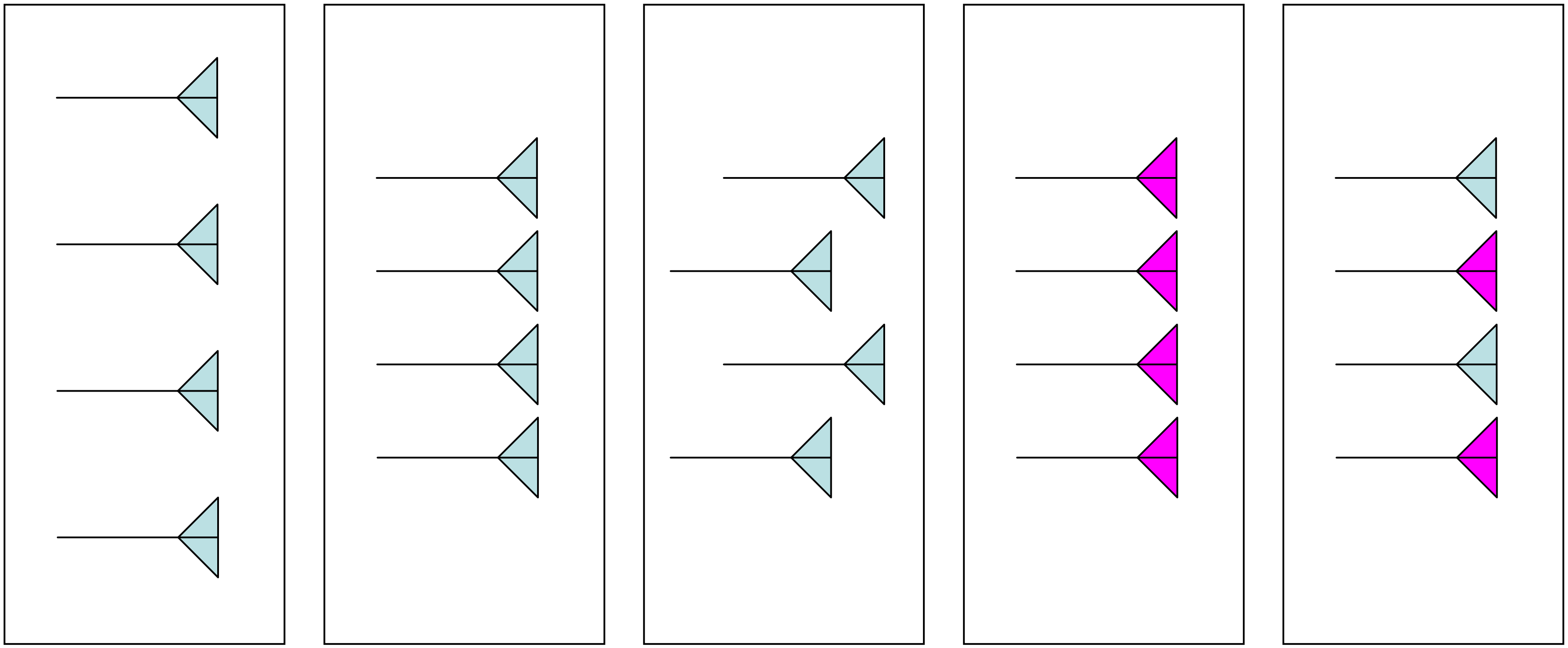
Double Directional Channel Model

… has been studied for MIMO systems

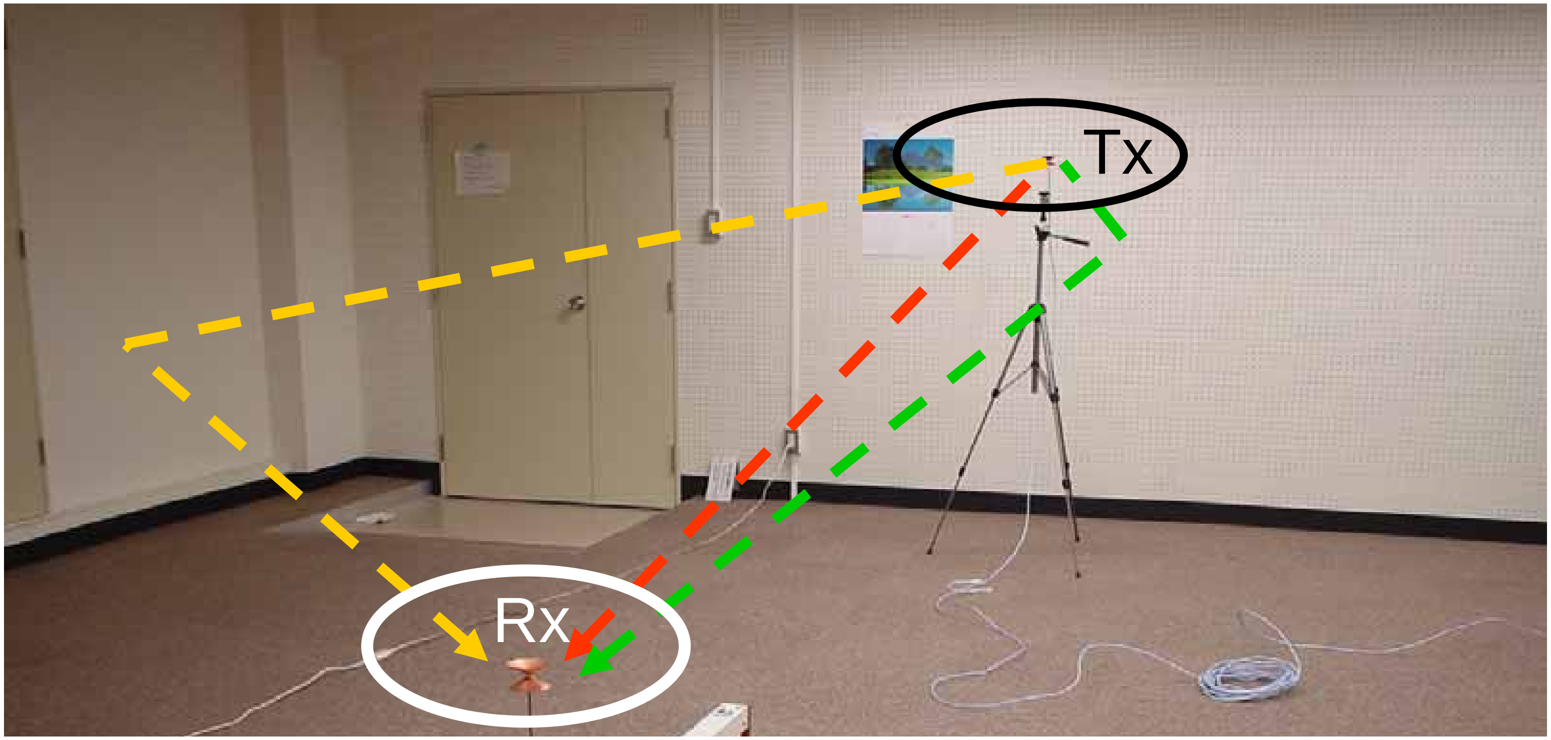


MIMO Antennas

Design of array antenna is a key issue of MIMO channel capacity.



MIMO Channel Matrix



$$\overline{\overline{H}}(f) = \oint_{Tx}\oint_{Rx} \overline{H}_{Rx}(f, \mathbf{\Omega}_{Rx}) H_{Multipath}(f, \mathbf{\Omega}_{Tx}, \mathbf{\Omega}_{Rx}) \overline{H}^{H}_{Tx}(f, \mathbf{\Omega}_{Tx}) \, d\mathbf{\Omega}_{Rx} \, d\mathbf{\Omega}_{Tx}$$

Rx antenna array vector

Tx antenna array vector

MIMO vs UWB

Antenna and propagation issues

	MIMO	UWB-IR
Antenna	Array configuration	Frequency distortion
Multipath	Double directional	
Magnitude	Frequency flat	Frequency dispersive

Propagation modeling approaches are the same.

UWB Channel Sounding

Time domain vs Frequency domain

	Time domain (Pulse)	Frequency domain (VNA)
Tx Power	Large	Small
Calibration	Difficult	Easy
Data processing	• Raw data • Deconvolution	• Fourier transform • Superresolution (subspace/ML)
Resolution	Fourier	High resolution

UWB Channel Sounding

Directive antenna vs Array antenna

	Directive antenna	Array antenna
Tx Power	Small	Large
Sync.	Timing	Timing and phase
Data processing	• Raw data • Deconvolution	• Fourier transform • Superresolution (subspace/ML)
Resolution	Fourier	High resolution

UWB Channel Sounding

Real array vs Synthetic array

	Real array	Synthetic array
Realization	Multiple antennas RF switch	Scanning
Measurement time	Short	Long
Mutual coupling	To be compensated	None
Antenna spacing	Limited by antenna size	No restriction

Summary: UWB Sounding Approach

- Double directional model

$$H_{\text{Multipath}}\left(f,\mathbf{\Omega}_{\text{Tx}},\mathbf{\Omega}_{\text{Rx}}\right)=$$

$$\sum_{l=1}^{L} a_l(f)\,\delta\left(\mathbf{\Omega}_{\text{Tx}}-\mathbf{\Omega}_{\text{Tx},l}\right)\delta\left(\mathbf{\Omega}_{\text{Rx}}-\mathbf{\Omega}_{\text{Rx},l}\right)\exp\left(-\mathrm{j}\,2\pi f\tau_l\right)$$

- Architecture
  - Frequency domain → – VNA
  - Synthetic array → – XY scanner
- Data processing
  - ML based super resolution

Summary: UWB Sounding Approach

- Pros and Cons
  - Short range ~ low power handling
    - Output power
    - Cable loss
  - Antenna scanning
    - Static environment
    - No array calibration

SAGE Algorithm for UWB (1)

SAGE Algorithm

- Widely adopted for wideband channel estimation

+

Novel UWB Signal Model

- Each path has
  - DOA and TOA : independent of the frequency
  - Path gain, phase rotation component : frequency dependent
- UWB signal is expressed as the superposition of conventional wideband signals

SAGE Algorithm for UWB (2)

- SAGE Algorithm
  - Search the parameters that maximize log-likelihood
  - Reduction of simultaneous search dimension
    - Derivation of complete data from incomplete data (EM)

$$\mathbf{y} \rightarrow \{\mathbf{x}_l\}_{l=1}^{L} \quad \text{(E-step)}$$

$$\arg\max_{\theta} \ln p(\mathbf{x}_l \mid \theta) \text{ for each } \mathbf{x}_l \quad \text{(M-step)}$$

    - Search in hidden data space = sequential search (SAGE)

SAGE Algorithm for UWB (3)

- Extension of SAGE Algorithm for UWB signal (1)
  - The log-likelihood of UWB signal: sum of log-likelihood in each subband
    - Log-likelihood function in conventional wideband signal

$$\ln p(\mathbf{x}_l \mid \theta) = \| \mathbf{x}_l - s \times \mathbf{a}_l(\theta) \|^2$$

s is assumed to be constant !!

    - However, in the UWB signal …

$$\ln p(\mathbf{x}_l \mid \theta) = \| \mathbf{x}_l - s(f) \times \mathbf{a}_l(\theta) \|^2$$

s is frequency dependent component !!

    - s is assumed to be constant within each subband

SAGE Algorithm for UWB (4)

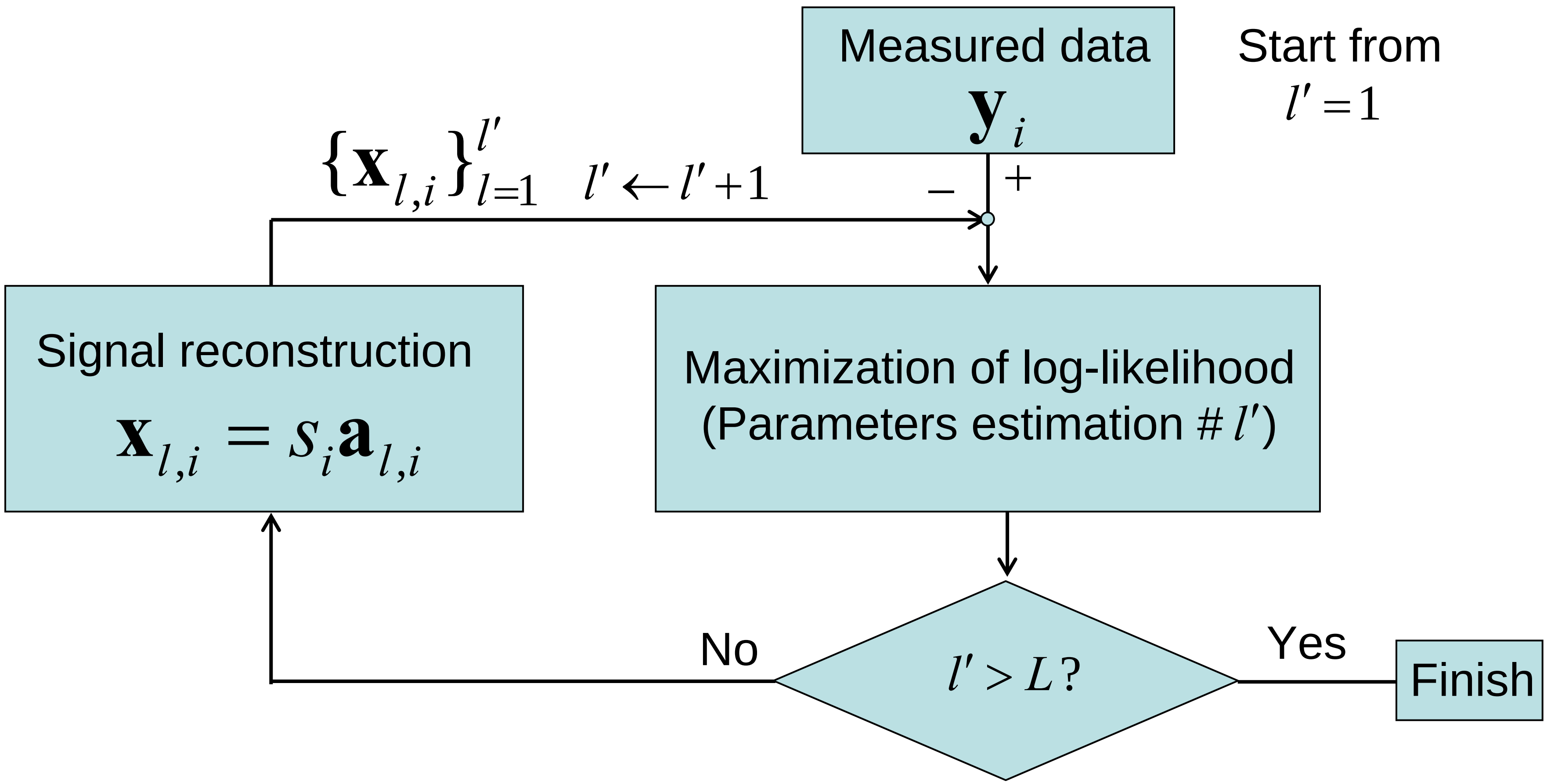
- Extension of SAGE Algorithm for UWB signal (2)
  - The log-likelihood of UWB signal:

$$\ln p(\{\mathbf{x}_{l,i}\}_{i=1}^{I} | \theta) = \sum_{i=1}^{I} \| \mathbf{x}_{l,i} - s_i \times \mathbf{a}_i(\theta) \|^2$$

  - The frequency dependent spectrum variation can be estimated as well as DoA and DT
  - The process of the algorithm can be regarded as the formulation of multi-dimensional matched filter
  - There are plenty ways of implementation of search as well as the initialization

SAGE Algorithm for UWB (5)

- One realization of the search (SIC-type)



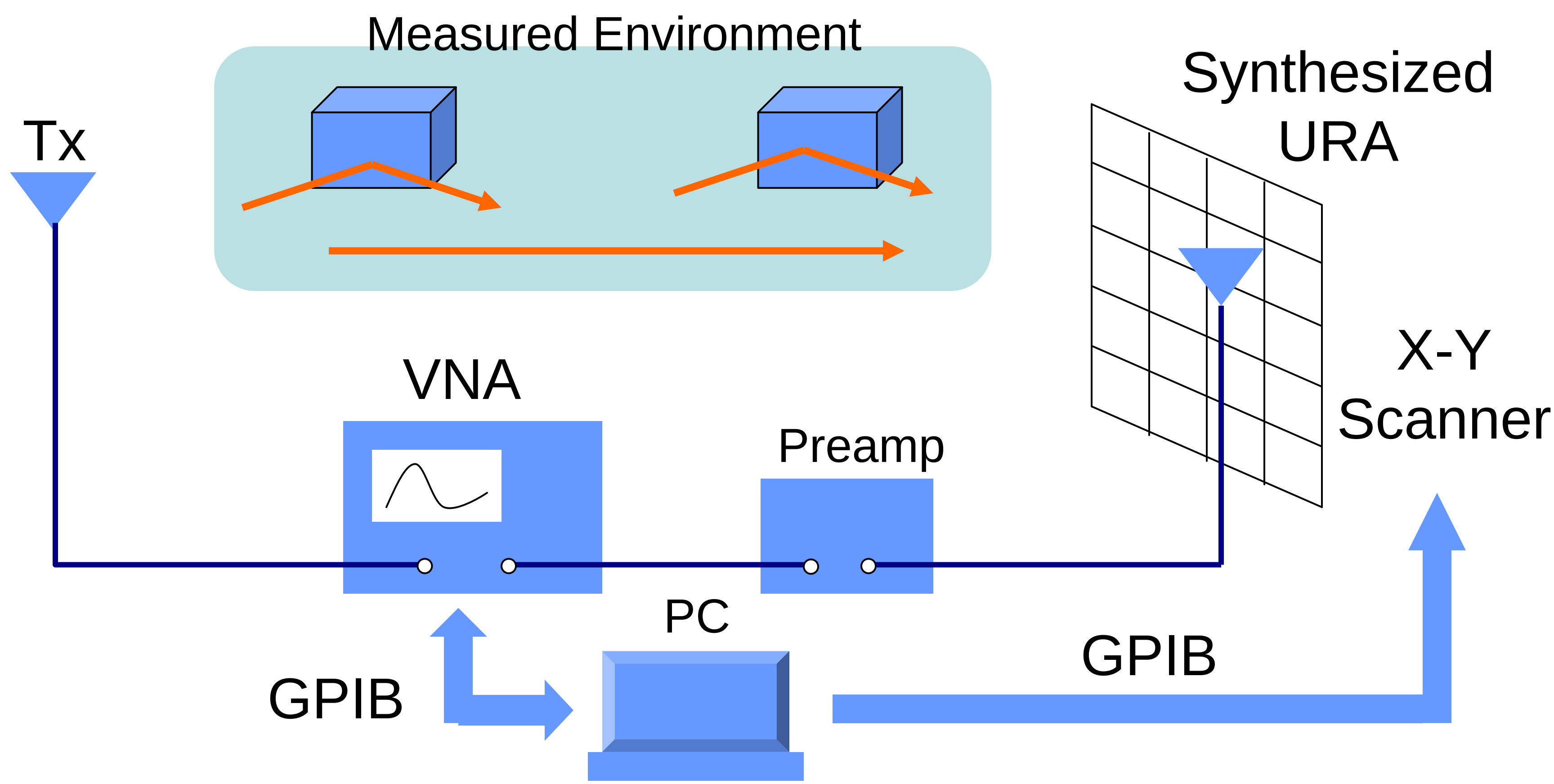
This is equivalent to the EM algorithm of the number of waves = 1.

SAGE Algorithm for UWB (6)

- Sensor-Clean vs. SAGE
  - Sensor-Clean (Cramer et al, 2002)
    - Beamforming + waveform estimation in time domain
    - Applicable even if the transmit waveform is unknown in receiver side
    - Require the time domain data (ex. with Digital Sampling Oscilloscope)
  - SAGE for UWB (Takada)
    - Beamforming + spectrum estimation in frequency domain
    - Applicable only when the transmit waveform is known in receiver side
    - The measurement is possible with Vector Network Analyzer Based system
    - Easy to deconvolute the antenna and propagation phenomena

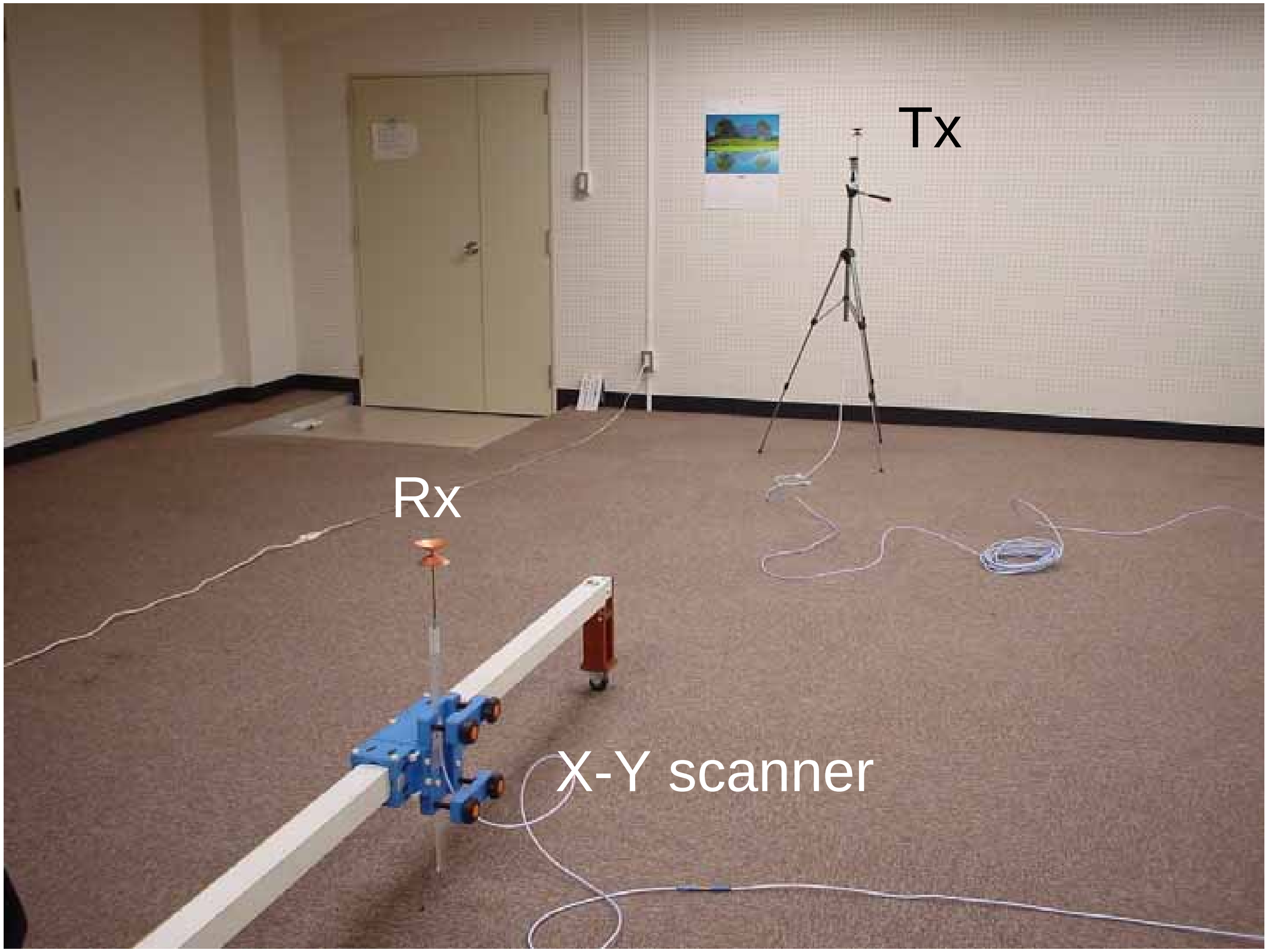
UWB Channel Sounding System

- System configuration: vector network analyzer based
  - Measurement of spatial transfer function automatically



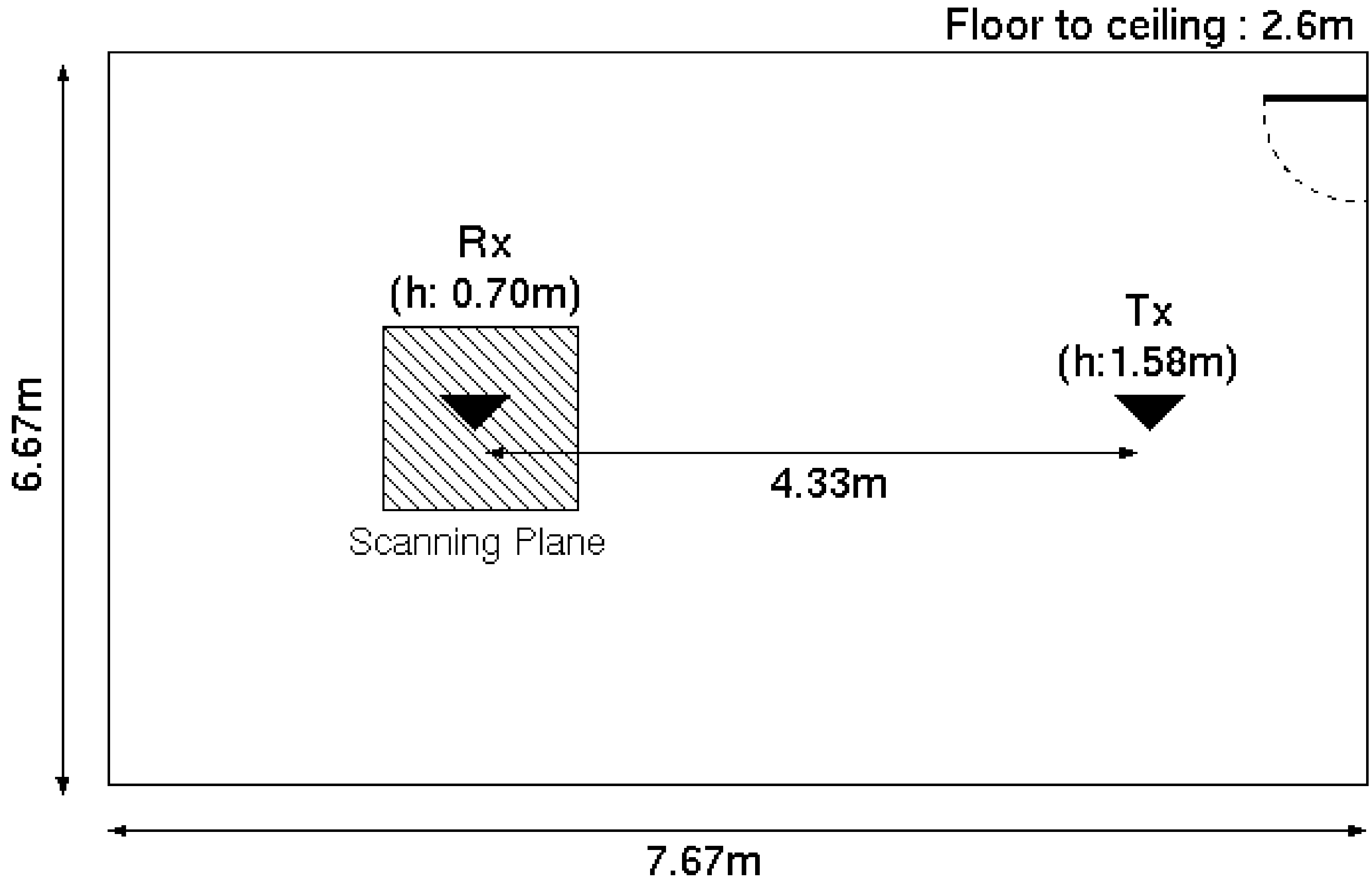
Experiment in an Indoor Environment (1)

- Measurement site: an empty room



Experiment in an Indoor Environment (2)

- Floor plan of the room

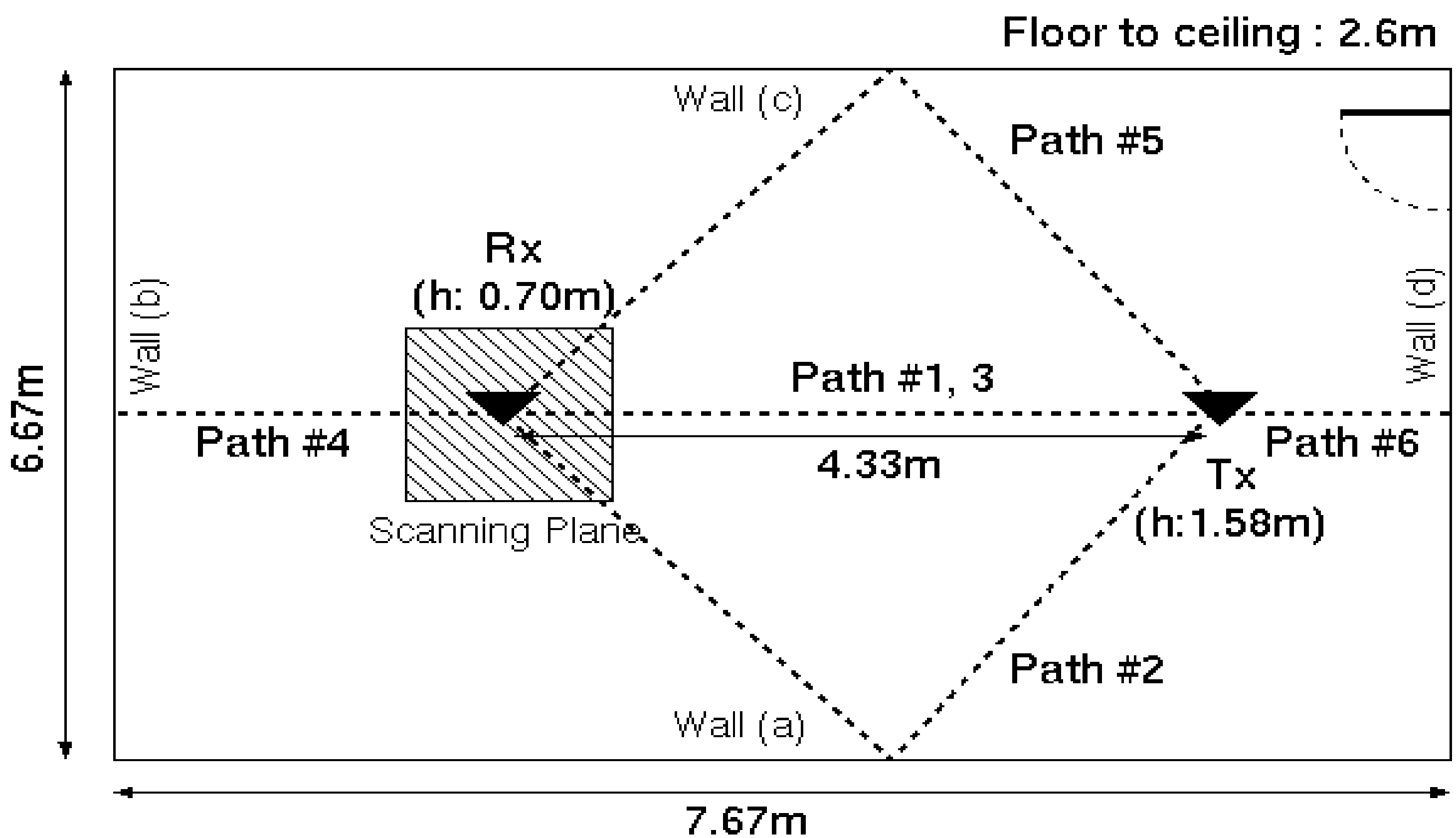


Experiment in an Indoor Environment (3)

- Estimated parameters : DoA (Az, El), DT
- Measured data :
  - Spatially 10 by 10 points at Rx
  - 801 points frequency sweeping from 3.1 to 10.6 [GHz] (sweeping interval: 10 [MHz])
- Antennas : Biconical antennas for Tx and Rx
- Calibration : Function of VNA, back-to-back
- IF Bandwidth of VNA : 100 [Hz]
- Wave polarization : Vertical - Vertical
- Bandwidth of each subband : 800 [MHz]

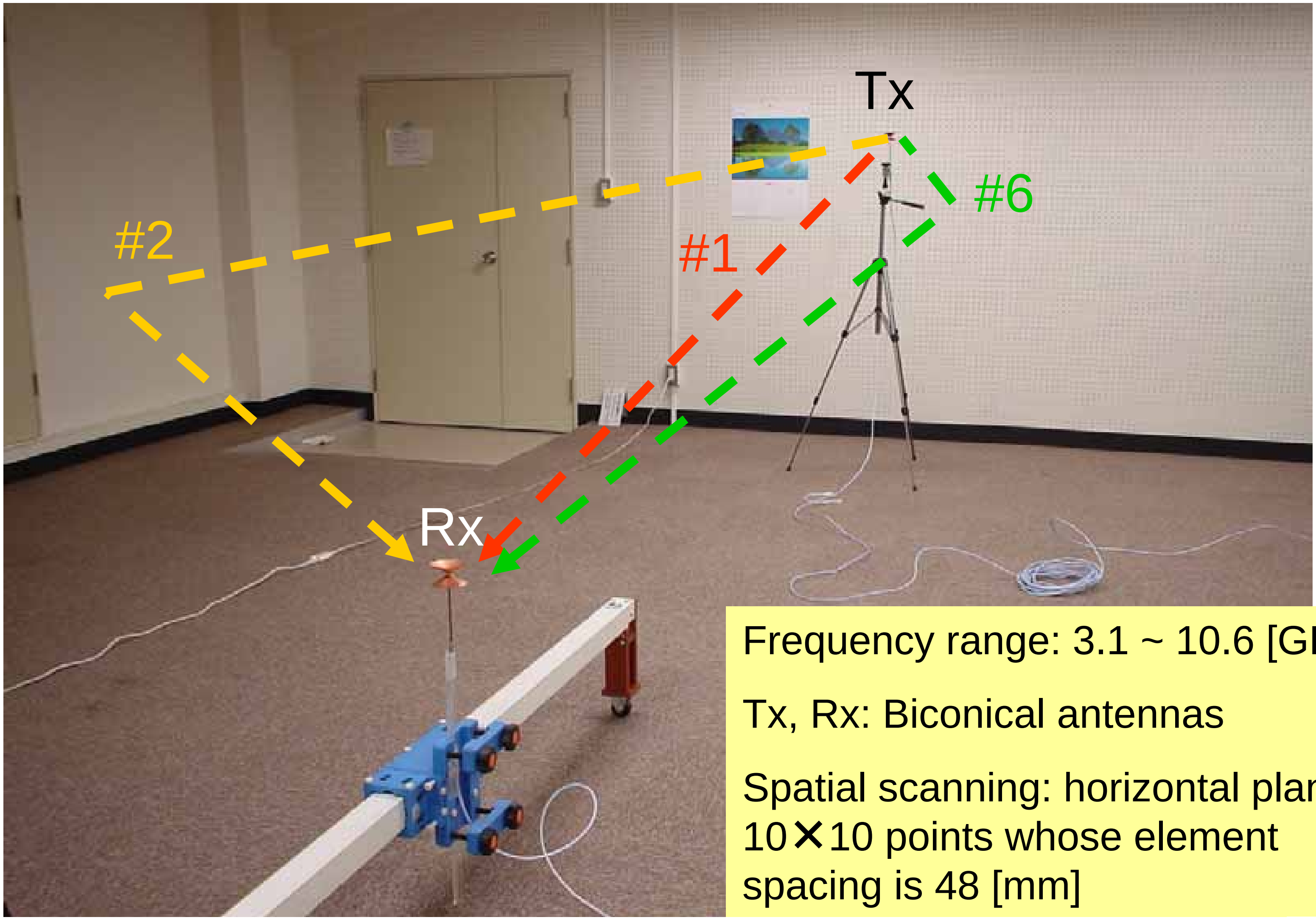
Measurement Result (1)

- The result of ray path identification



There 6 waves detected and are almost specular waves.

Measurement Result (2)



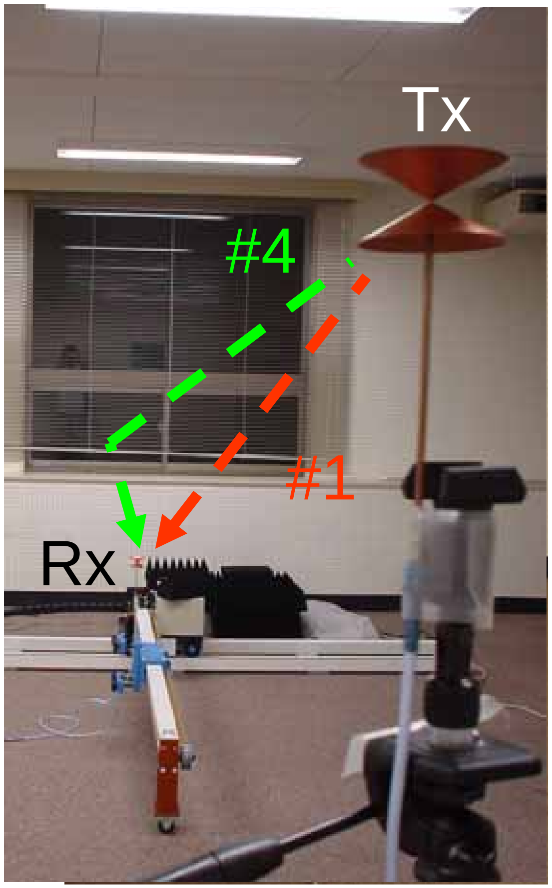
Frequency range: 3.1 ~ 10.6 [GHz]

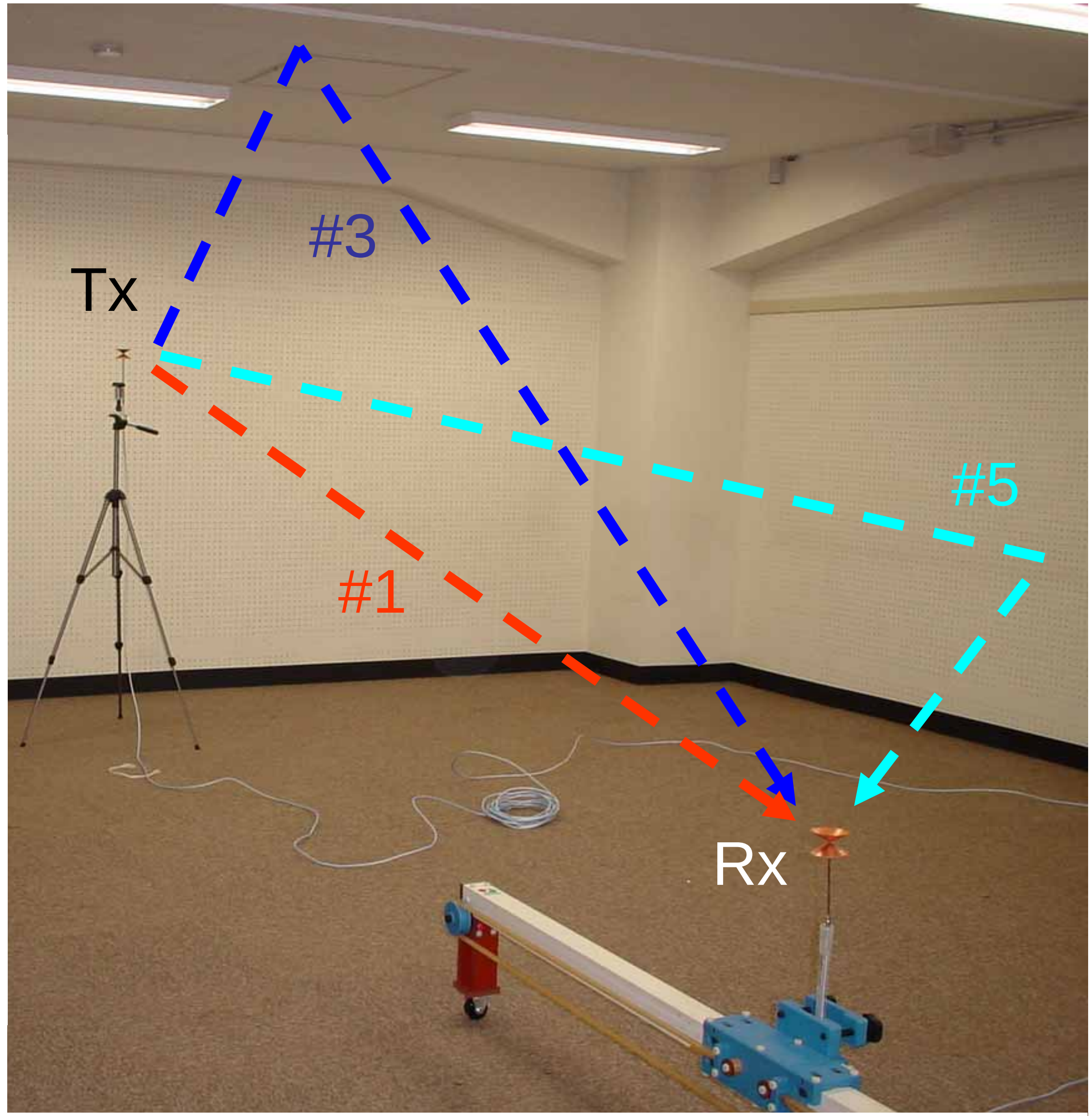
Tx, Rx: Biconical antennas

Spatial scanning: horizontal plane, 10×10 points whose element spacing is 48 [mm]

6 specular waves were observed.

Measurement Result (3)

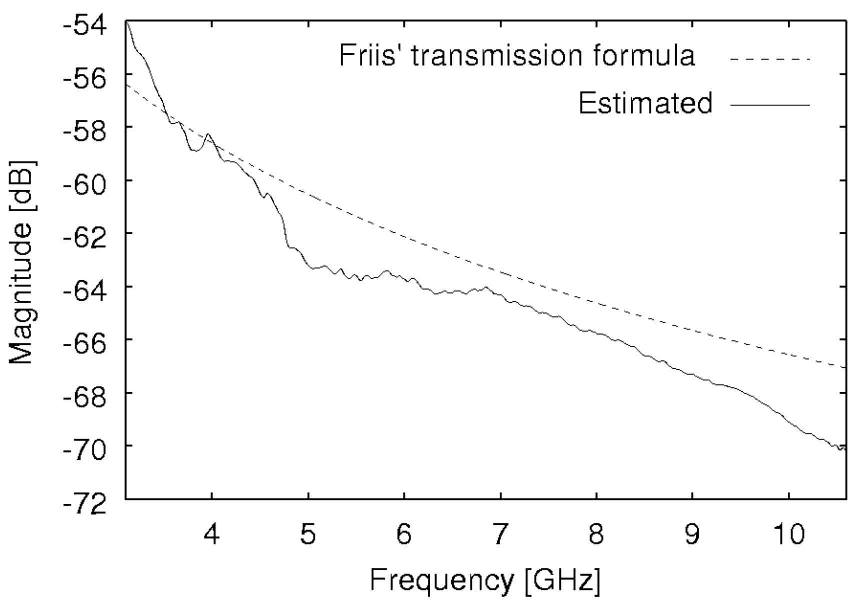


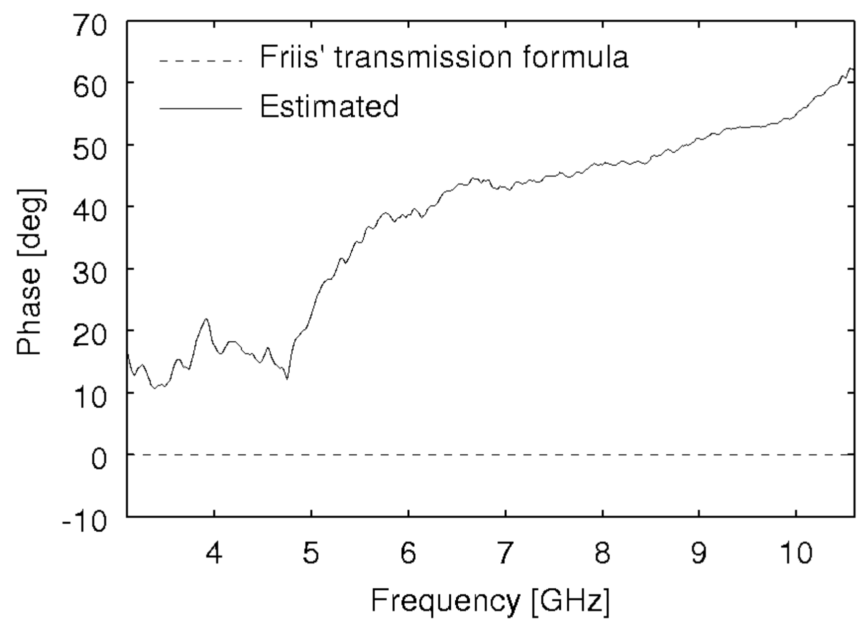


#4 is a reflection from the back of Rx

Measurement Result (4)

- Extracted spectrum of direct wave

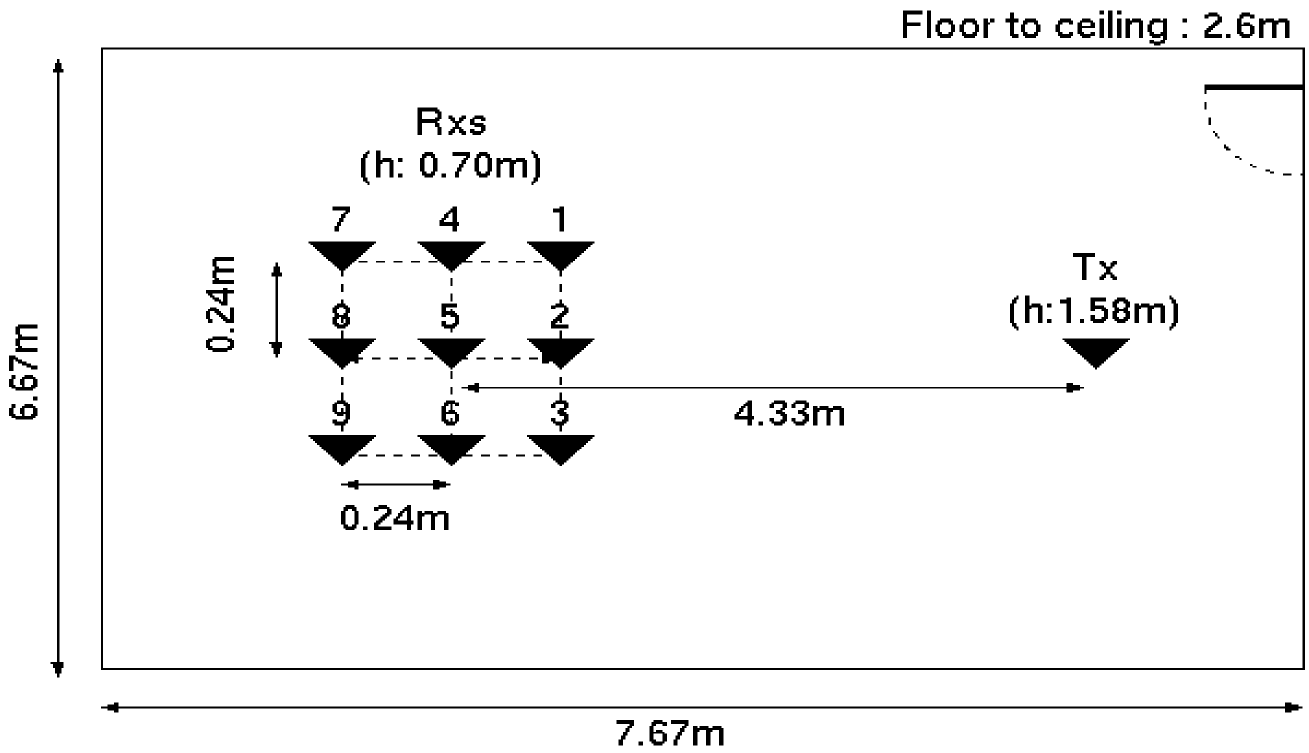




- – Transfer functions of antennas are already deconvolved.
- – The phase component is the deviation from free space phase rotation (ideally flat).

Experiment in an Indoor Environment (4)

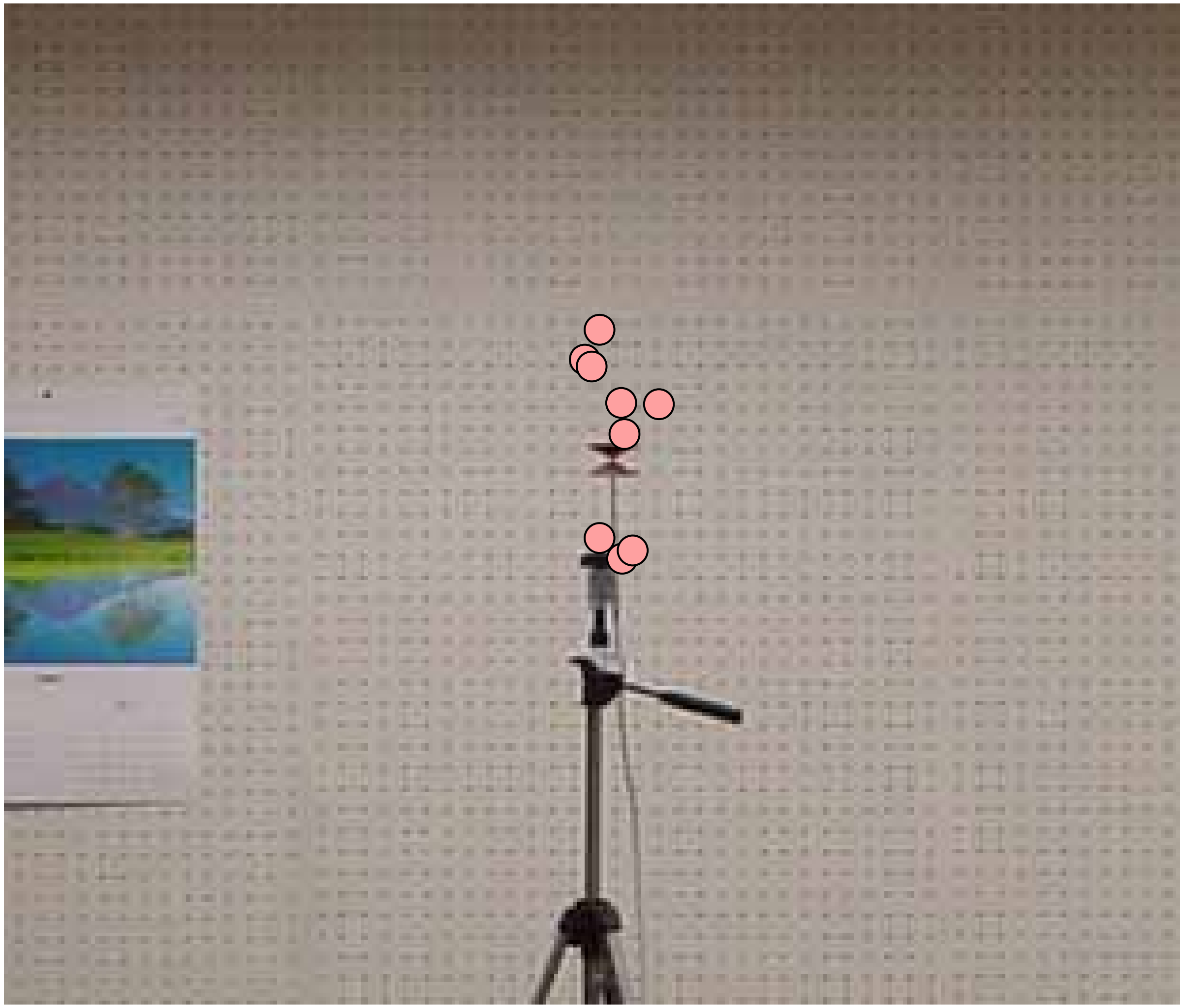
- Comparison of the measurement result in 9 different Rx position



The path type detected in each measurement was almost same.

Measurement Result (5)

- Estimated source position for direct wave

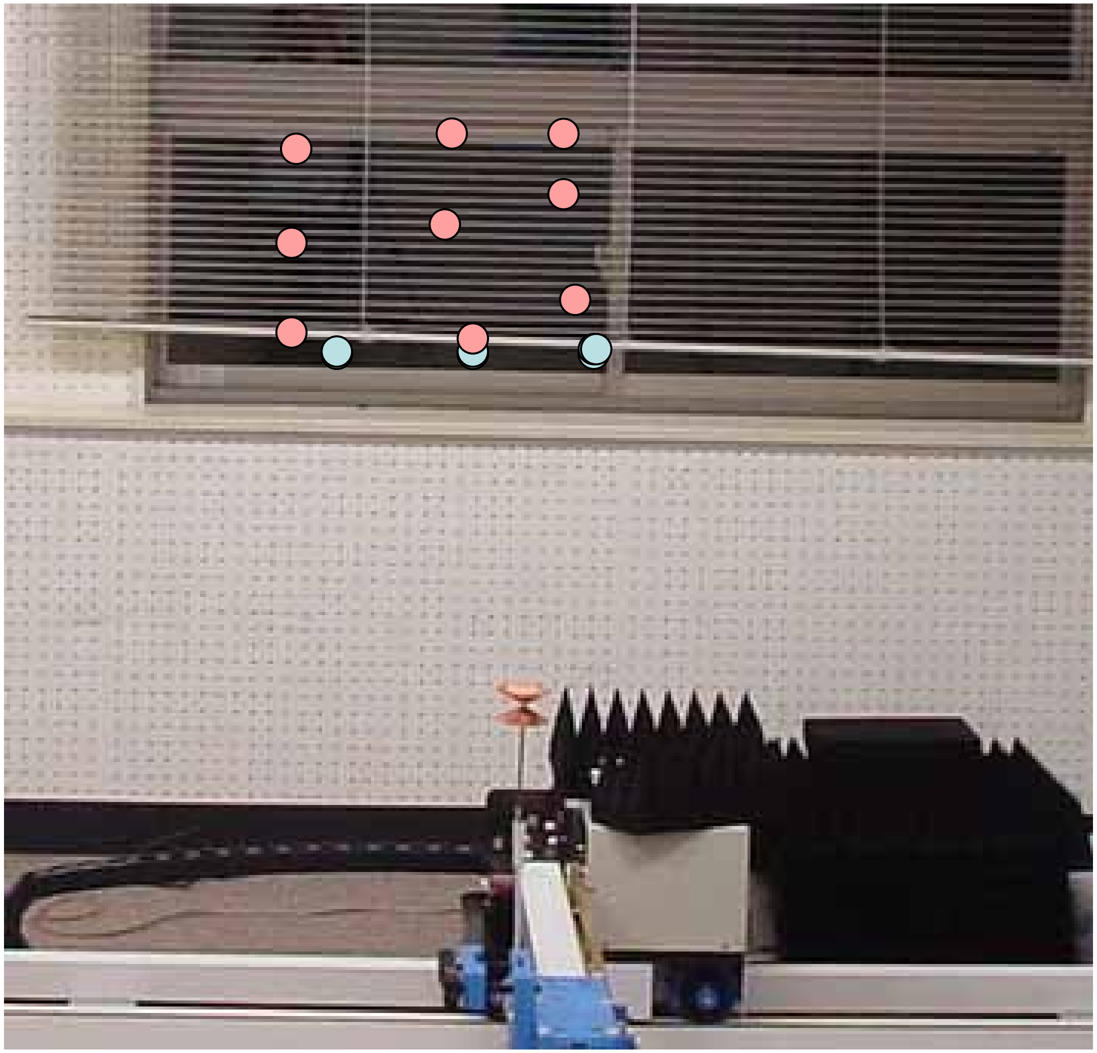


Maximum deviation is 17cm from source point.

Estimated by measurement

Measurement Result (6)

- Estimated reflection points in back wall reflection



All the reflection points are above those predicted by GO.

Predicted by GO

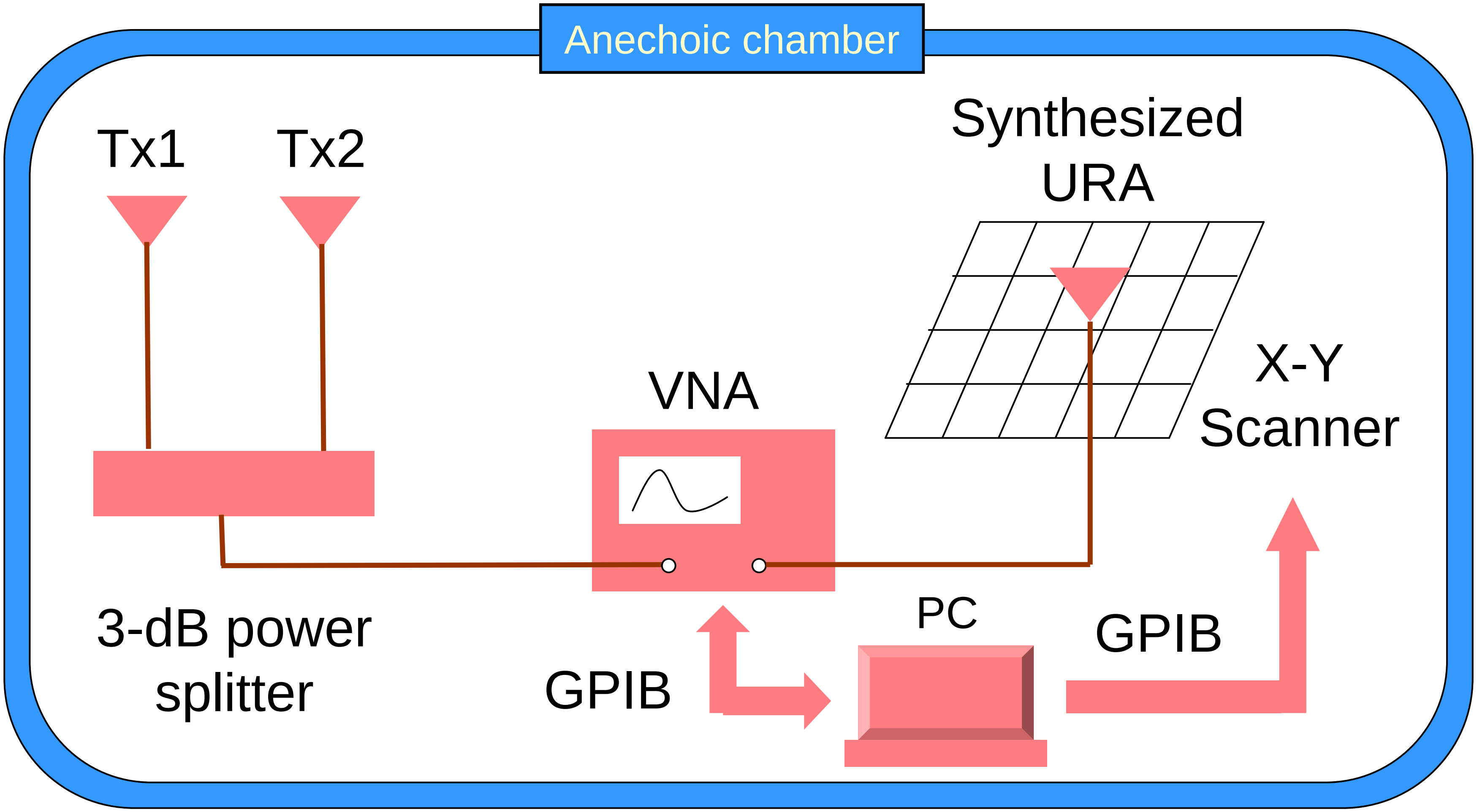
Estimated by measurement

Discussion

- Some problems have been appeared.
  - 2 ~ 4 spurious waves detected during the estimation of 6 waves
  - Residual components after removing dominant paths
  - Signal model error (plane or spherical)
  - Estimation error based on inherent resolution of the algorithm implementation
  - Many distributed source points (diffuse scattering)

➡ Further investigation in simple environment

Performance Evaluation in Anechoic Chamber



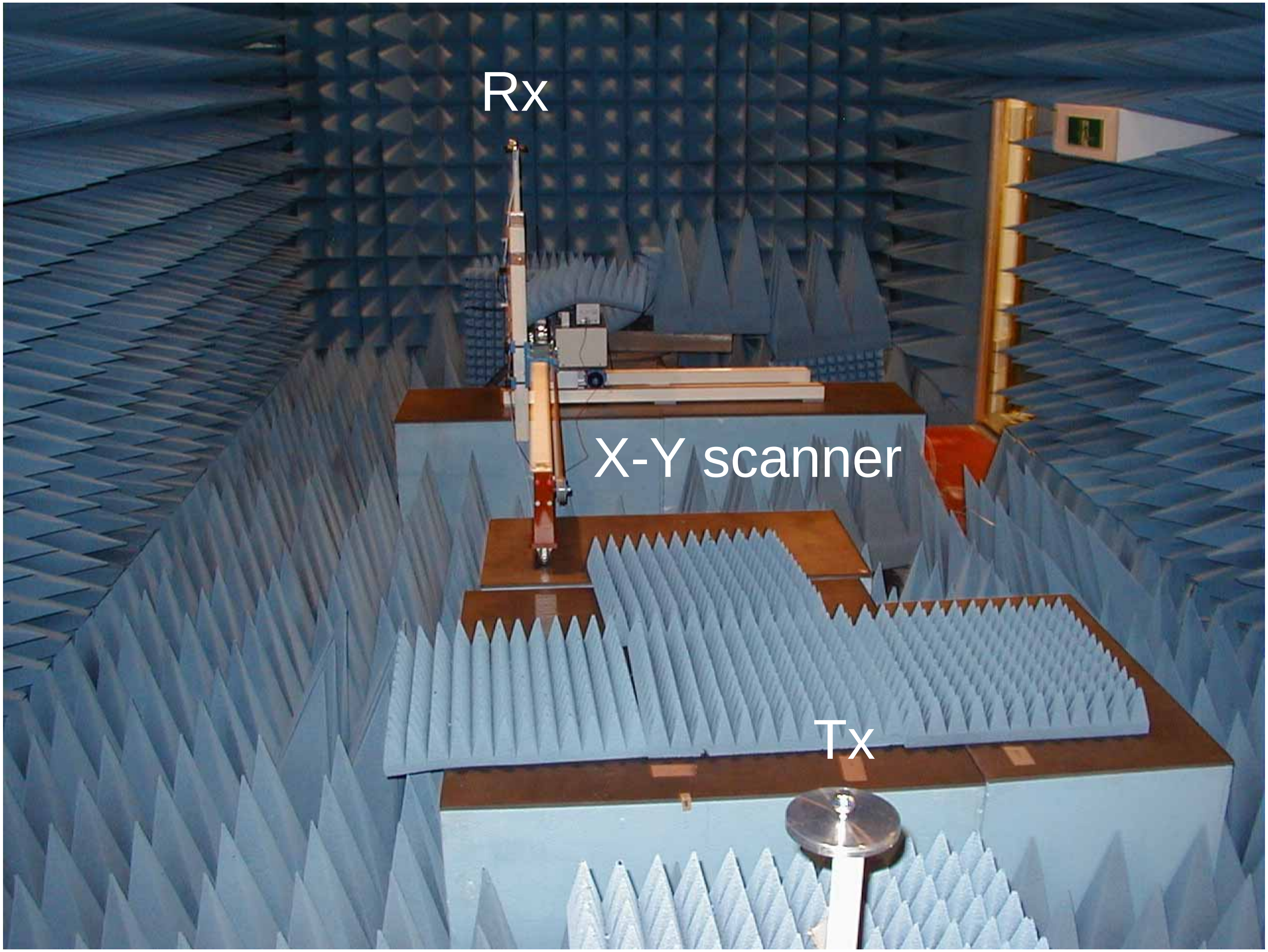
Specifications of Experiment

- Frequency : 3.1 ~ 10.6 GHz
  - 0.13 ns Fourier resolution
- Antenna scanning plane : 432 mm square in horizontal plane
  - 10 deg Fourier resolution
  - 48 mm element spacing
    (less than half wavelength @ 3.1 GHz)
- Wideband monopole antennas were used
  - Variation of group delay < 0.1 ns within the considered bandwidth
- SNR at receiver：About 25 dB

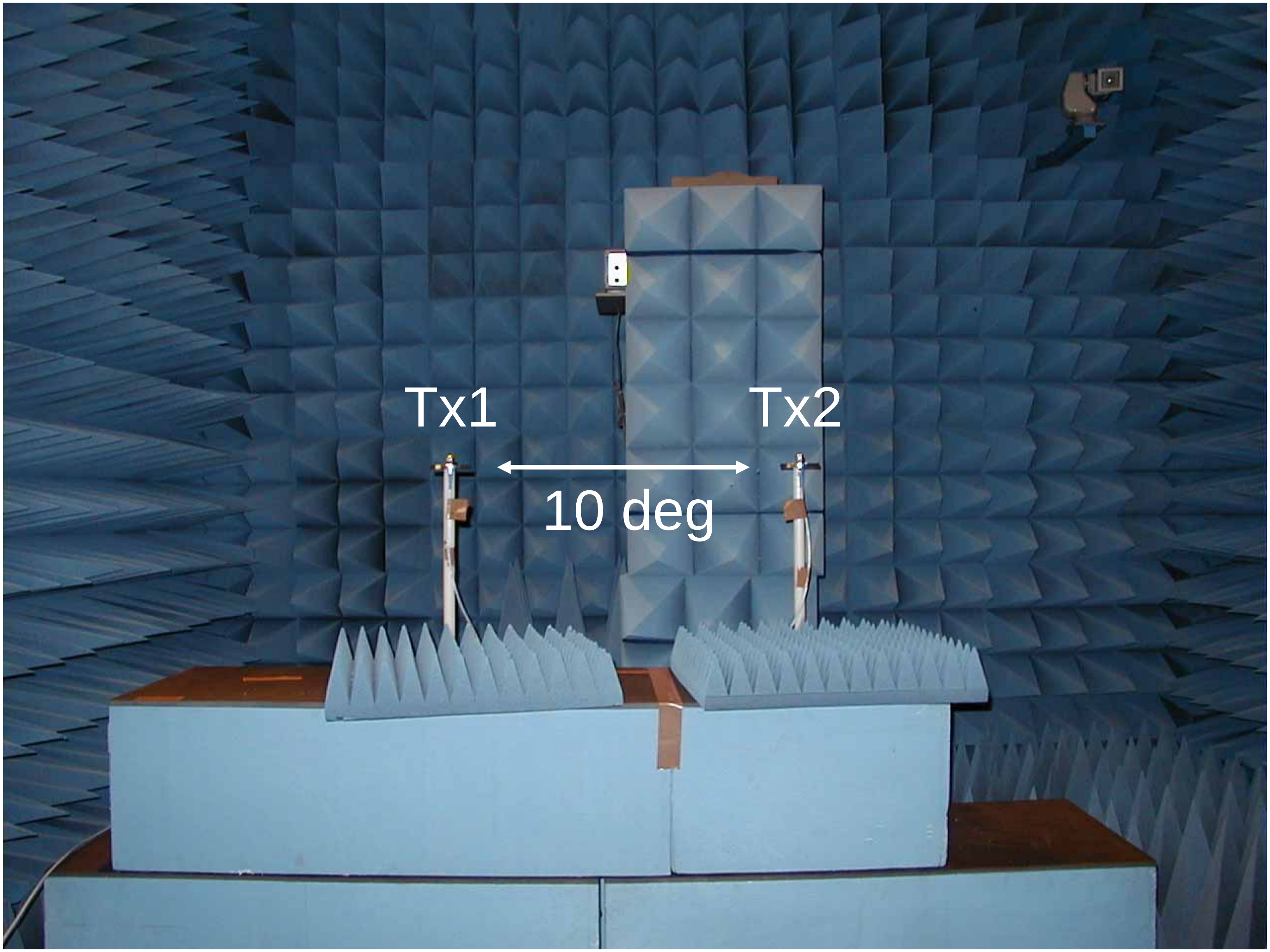
Aim of Anechoic Chamber Test

- Evaluation of spatio-temporal resolution
  - Separation and detection of two waves that
    - Spatially 10 deg different and same DT
    - Temporally 0.67 ns (= 20 cm) different and same DoA

Setup of Experiment

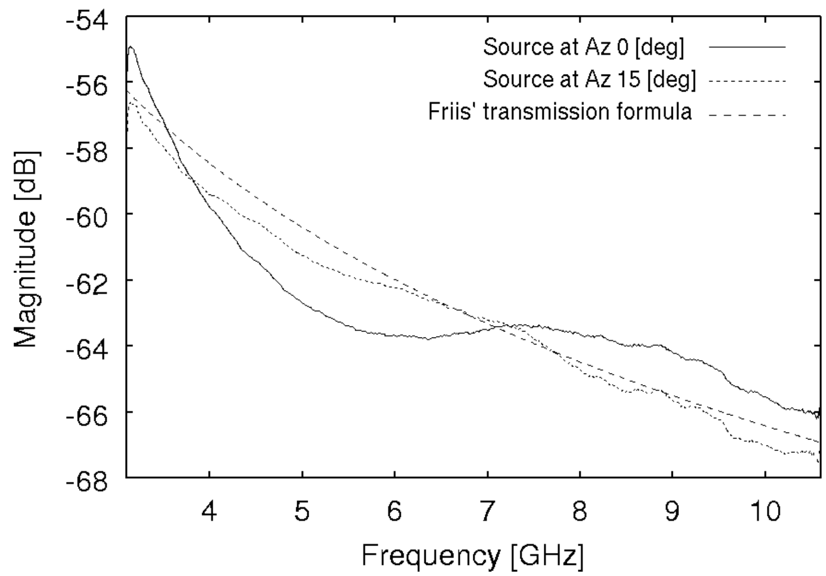


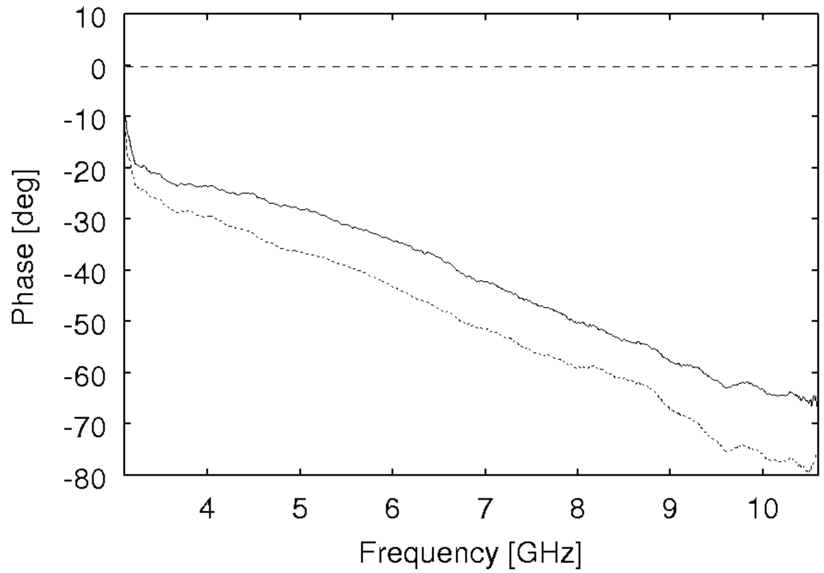
Spatial Resolution Test (1)



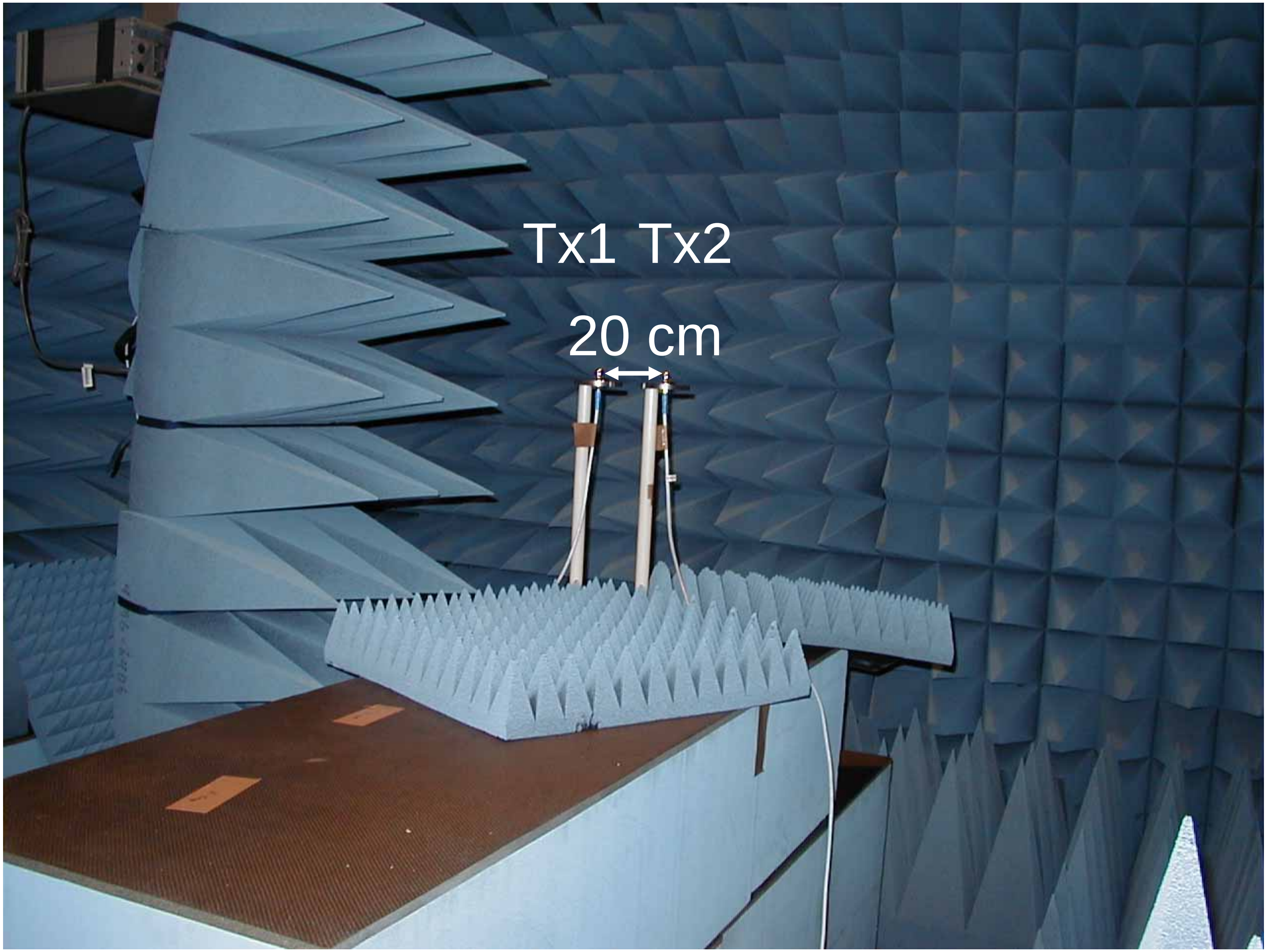
Spatial Resolution Test (2)

- 10 deg separated waves are accurately separated.
  - Parameters and spectra are accurately estimated.
  - The estimated phase denotes a deviation from free space phase rotation (~ 3 mm).
  - Antenna characteristics are already deconvolved.





Temporal Resolution Test (1)

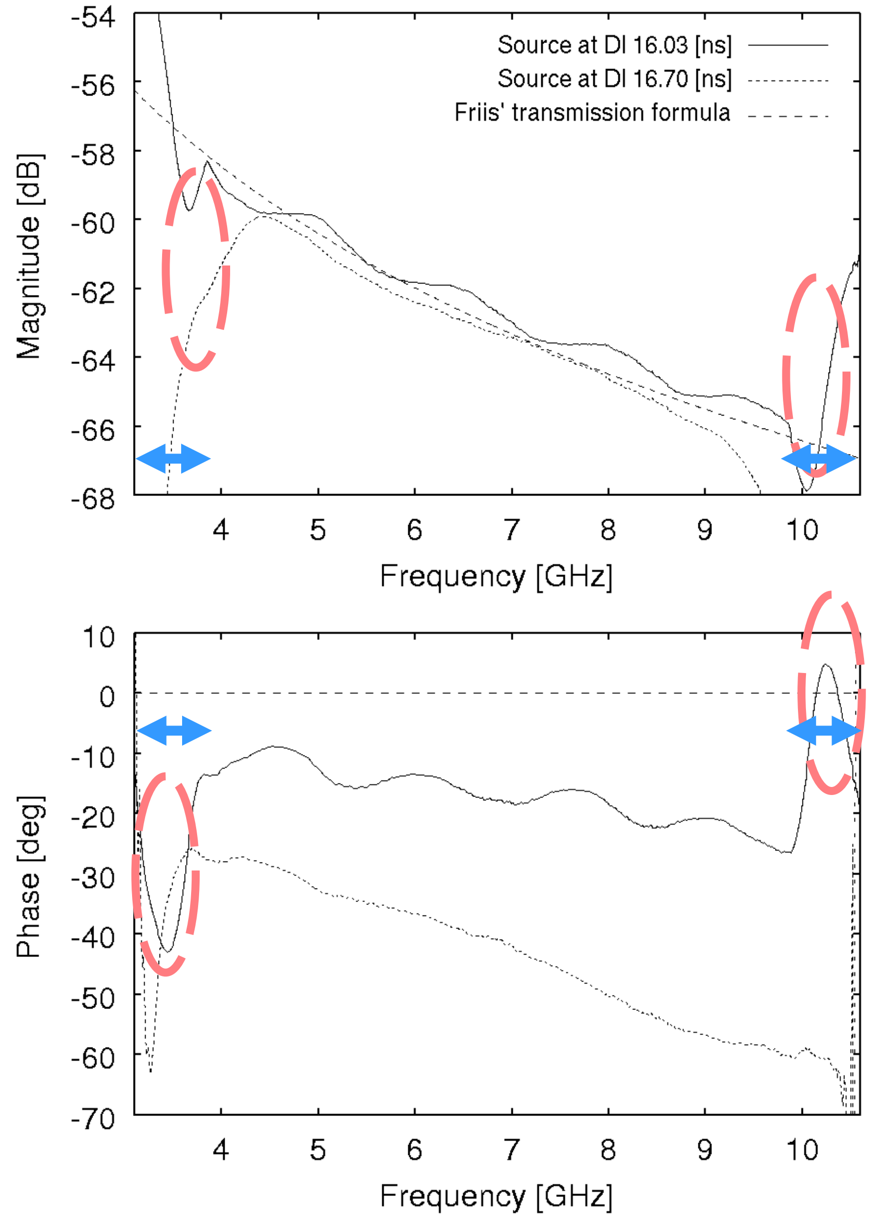


Temporal Resolution Test (2)

- 0.67 ns separated waves are accurately resolved.
  - Subband width：1.5 GHz
  - Spectrum estimation is impossible in the higher and lower frequency region of

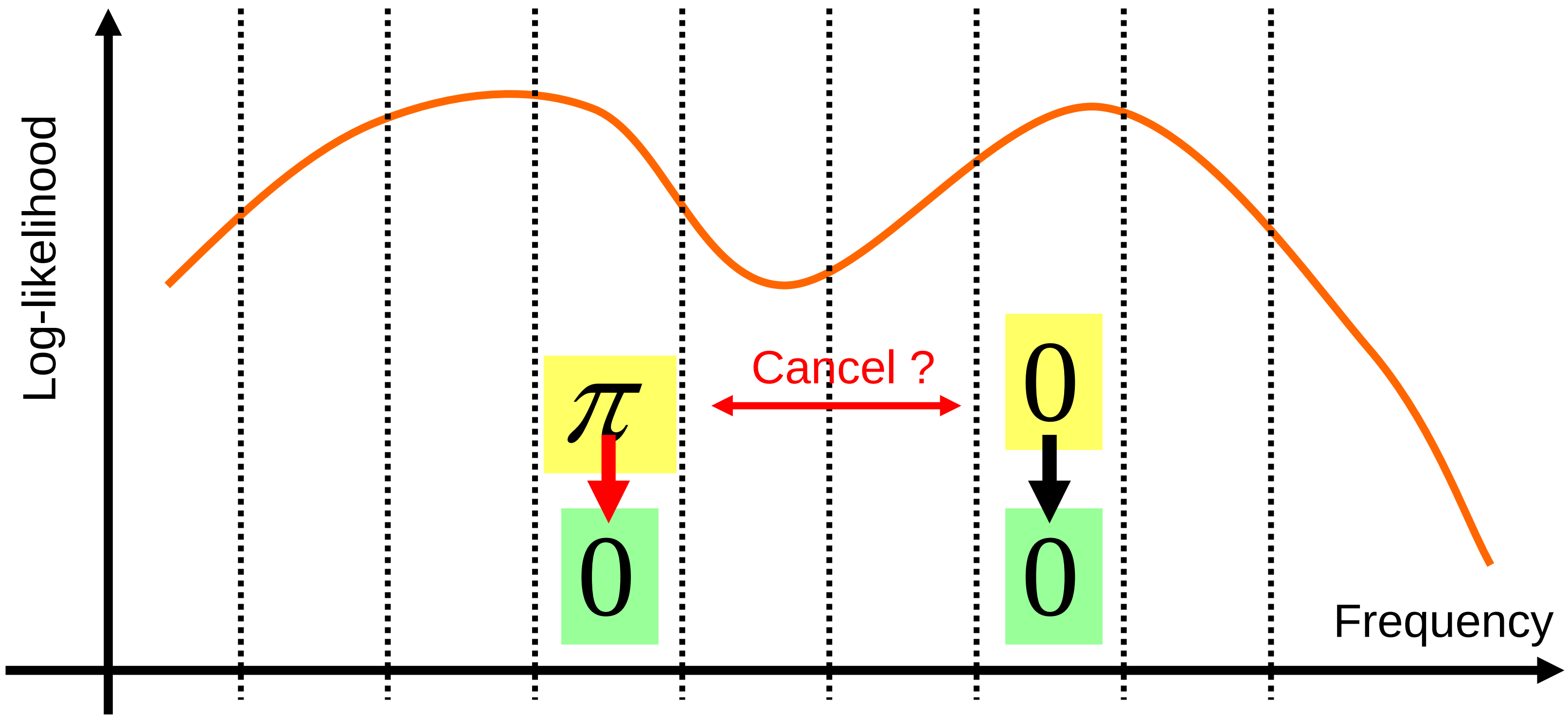
$$\left(\frac{1}{\Delta\tau = 0.67\,[\mathrm{ns}]} \right) \Big/ 2$$

$$= 0.75\,[\mathrm{GHz}]$$



Subband Processing (1)

- … relieves a bias of parameter estimation due to amplitude and phase fluctuation within the band
- Tradeoff between the resolution and accuracy of parameter estimation: some optimization is needed !!



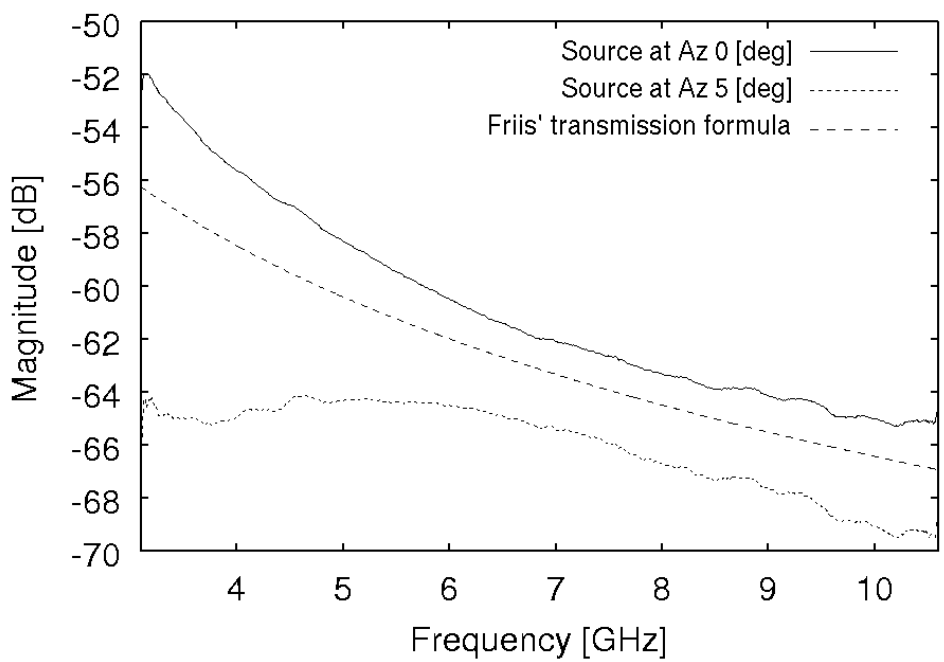
Subband Processing (2)

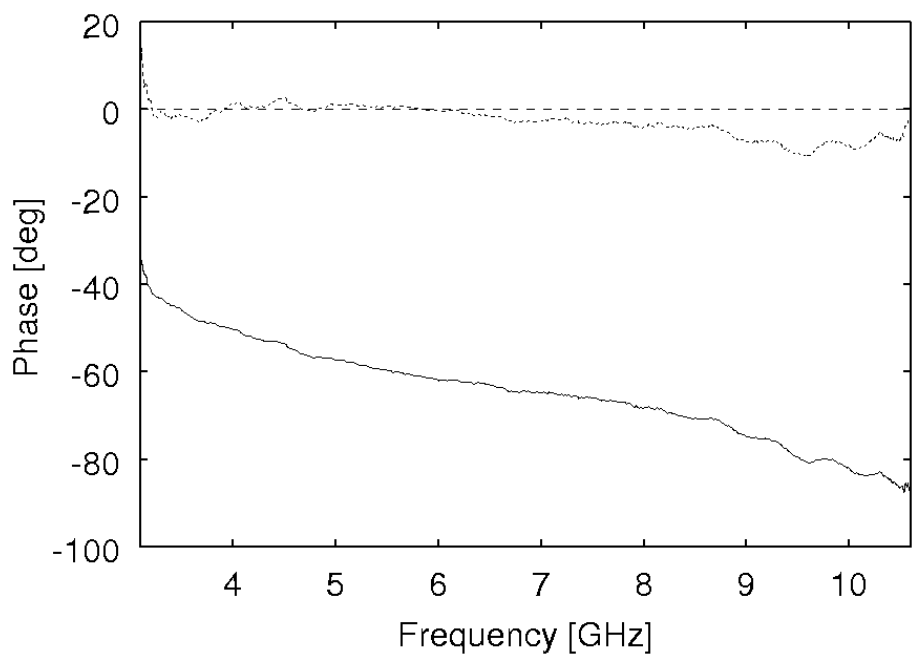
- How to choose the optimum bandwidth of subband?
  - Suppose two waves are $\Delta\theta$ and $\Delta\tau$ separated

<table>
<tr><td rowspan="2" colspan="2"></td><td colspan="2">Angle resolution : θ_{res}</td></tr>
<tr><td>$\theta_{\text{res}} < \Delta\theta$</td><td>$\theta_{\text{res}} > \Delta\theta$</td></tr>
<tr><td rowspan="2">Delay resolution τ_{res}</td><td>$\tau_{\text{res}} < \Delta\tau$</td><td rowspan="2">Bandwidth within which deviation of antennas and propagation characteristics is sufficiently small</td><td>$\approx \dfrac{1}{\Delta\tau}$</td></tr>
<tr><td>$\tau_{\text{res}} > \Delta\tau$</td><td>Impossible to resolve</td></tr>
</table>

Subband Processing (3)

- Behavior for the detection of two waves closer than the inherent resolution of the algorithm
  - Regard two waves as one wave (ex. same incident angle)
  - Two separated waves, but biased estimation of power (ex. 5 deg different incident angles)

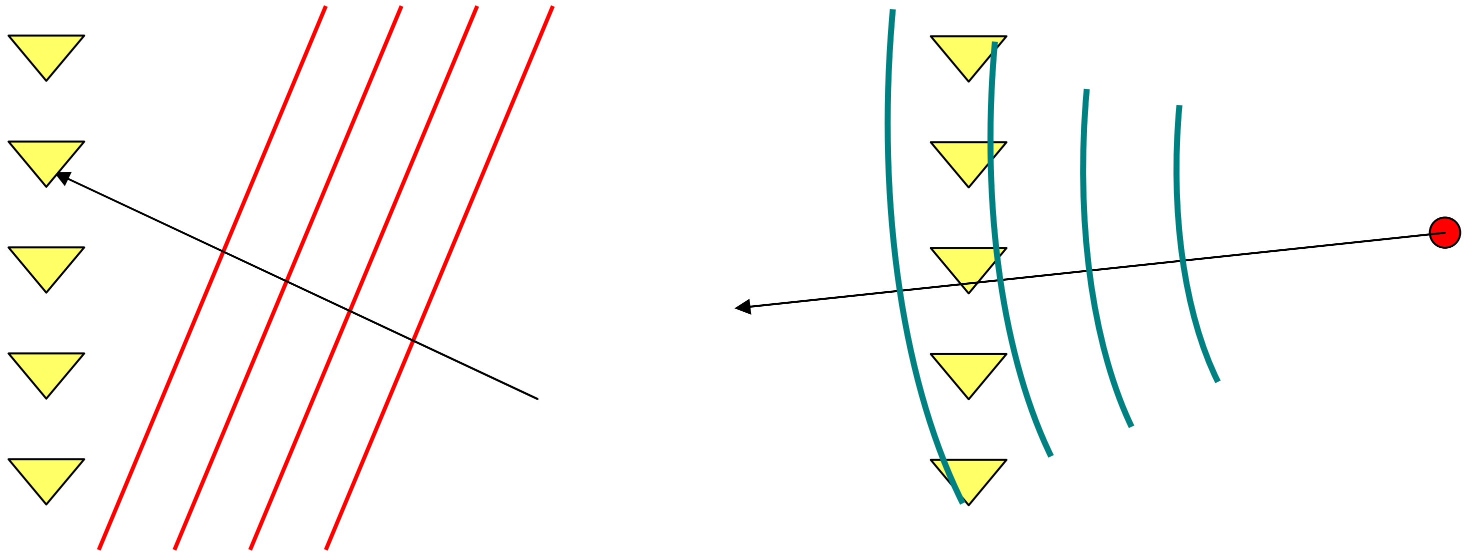




Deconvolution of Antenna Patterns

- Deconvolution of antennas
  - Construction of channel models independent of antenna type and antenna configuration
  - Deconvolution is post-processing (from the estimated spectrum by SAGE)
    - Simple implementation rather than the deconvolution during the search

Spherical vs Plane Wave Models (1)



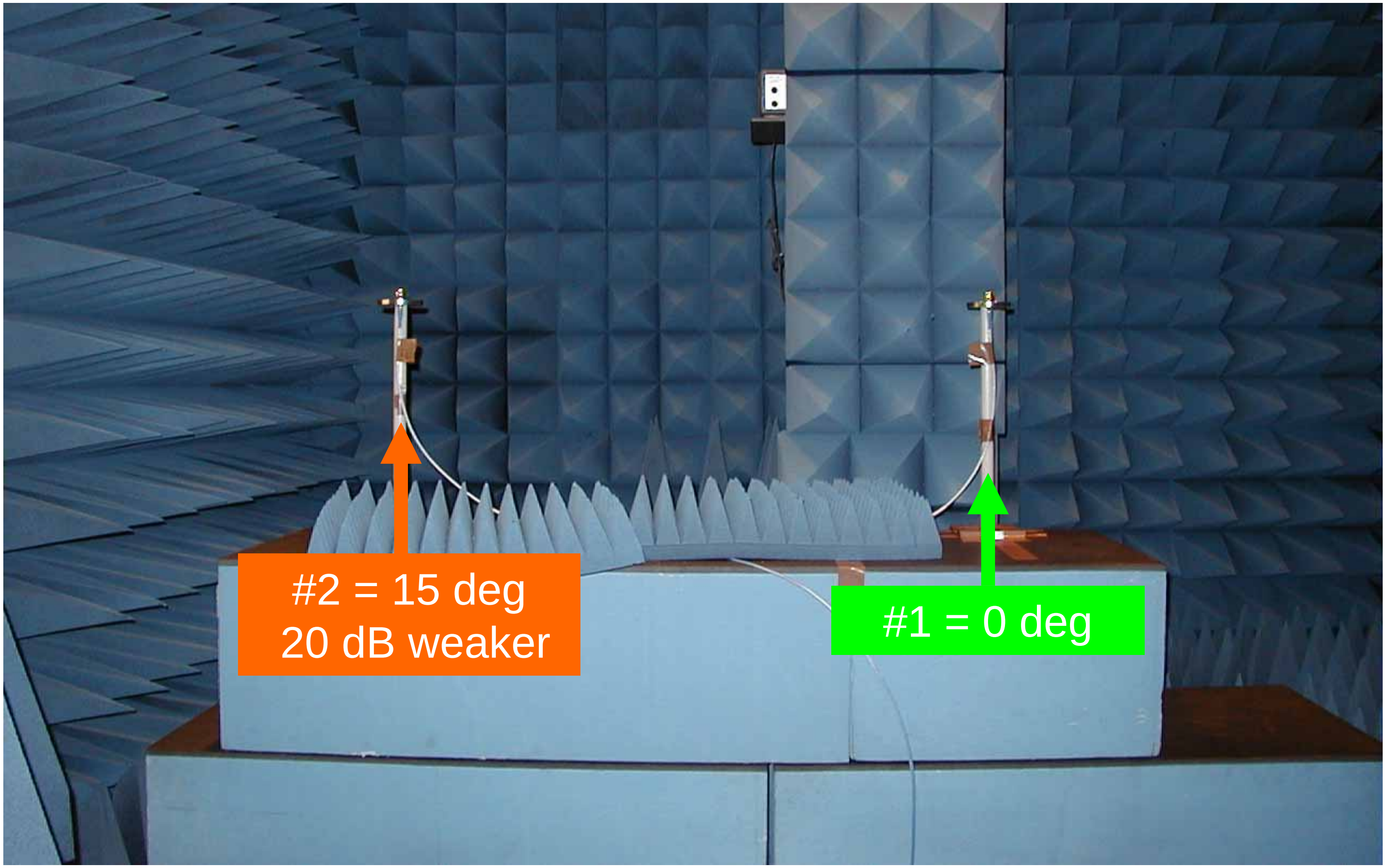
Plane wave incidence
(far field incidence)

Spherical wave incidence
(radiation from point source)

- How these models affect for the accurate estimation?
  - Spurious (ghost path) and detection of weak paths
  - Empirical evaluation of model accuracy

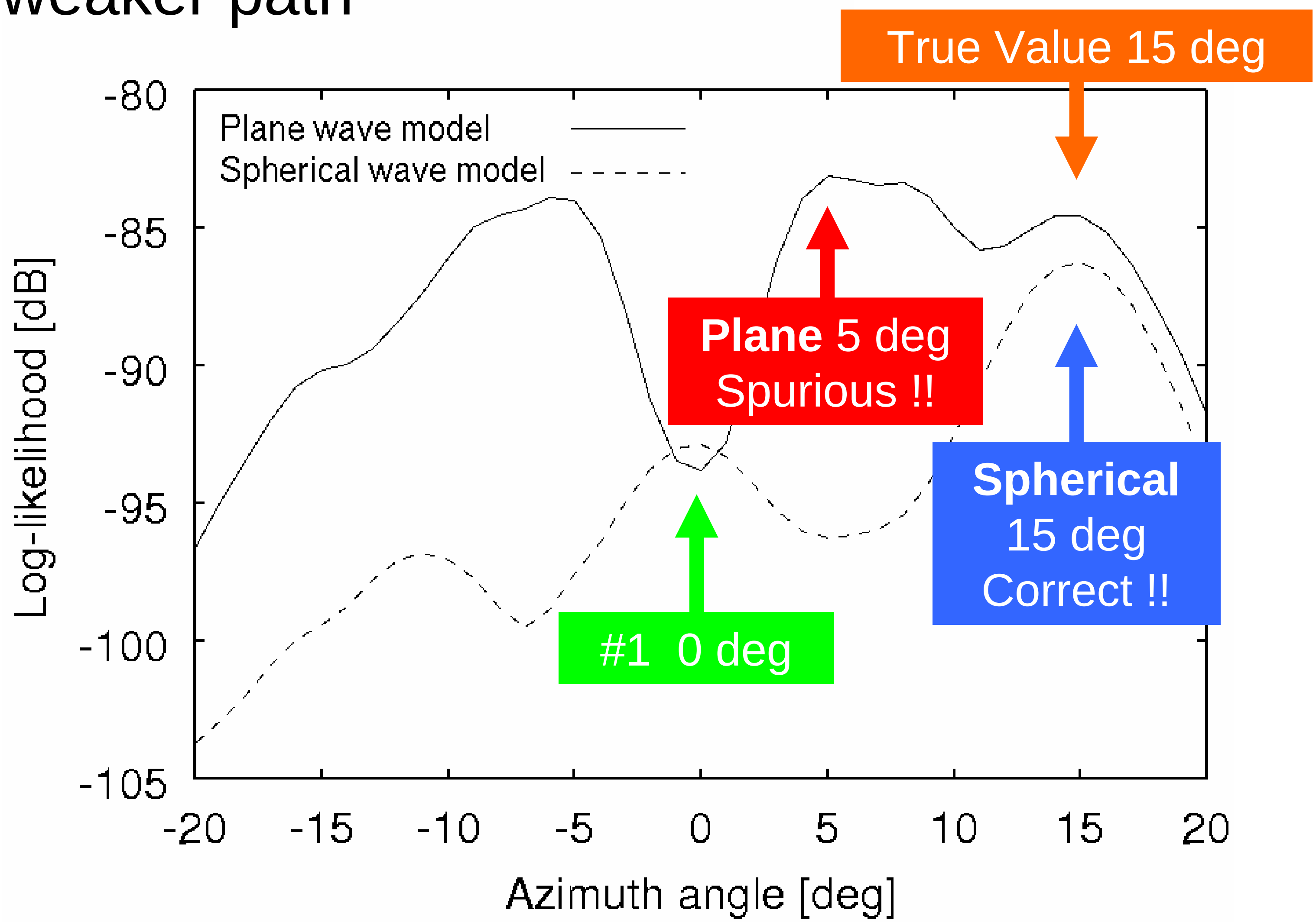
Spherical vs Plane Wave Models (2)

- Detection of 20 dB different two waves
  - Is a weaker source correctly detected?



Spherical vs Plane Wave Models (3)

- Log-likelihood spectrum in the detection of weaker path



Summary of Evaluation Works (1)

- Evaluation of the proposed UWB channel sounding system in an anechoic chamber
  - Resolved spatially 10 deg, temporally 0.67 ns separated waves
  - Spectrum estimation is partly impossible in the highest and lowest frequency regions of $\frac{1}{2\Delta\tau}$.
  - The algorithm treats two waves closer than inherent resolution as one wave, or results in biased power estimation even if they are separated.

Summary of Evaluation Works (2)

- For reliable UWB channel estimation with SAGE algorithm
  - An optimum way to choose the bandwidth of subband
  - The number of waves estimation is done by SIC- type procedure
- Deconvolution of antennas effects from the results of SAGE
  - For channel models independent of antennas

Summary of Evaluation Works (3)

- Spherical incident wave model is more robust than plane wave incident model
  - Spurious reduction is expected
  - Effective in the detection of weaker path

Summary of This Talk

- Antennas and propagation of UWB
  - Necessity of double directional propagation model
- UWB double directional sounder
  - VNA
  - XY scanner
  - ISI-SAGE (ML based)
- Initial indoor experiment
- Performance evaluation

Future Tasks

- Double directional and polarimetric extension
  - Double directional measurement has started.
  - Extension of estimation program to SIMO to MIMO.
- More field measurements
  - Office
  - Home

Acknowledgement

- Thanks to
  - Mr. Katsuyuki Haneda for help of preparation.
  - Prof. Kiyomichi Araki and Prof. Takehiko Kobayashi for discussion and suggestion.

Notice

- The slides include some recent unpublished results, and re-distribution of the slides is not permitted.