Modeling Environmental Effects on Directionality in Wireless Networks

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26 June 2009

Outline

1. Radio Propagation Environments and Directional Antennas
   - Pretty Pictures
   - Measuring Effective Directionality
   - Accuracy of Current Models
2. Estimating Radio Propagation
   - Ray Tracing
   - Propagation Models
   - Directivity Models
3. Directivity and Propagation are not Orthogonal
   - What's Missing?
4. Modeling
   - Fitting Specific Environments
   - Fitting Types of Environments
   - Relating Signals to Environment Parameters

RF Propagation Environments

RF Propagation Environments

Measurement Processes [1/2]

Baseline Measurements

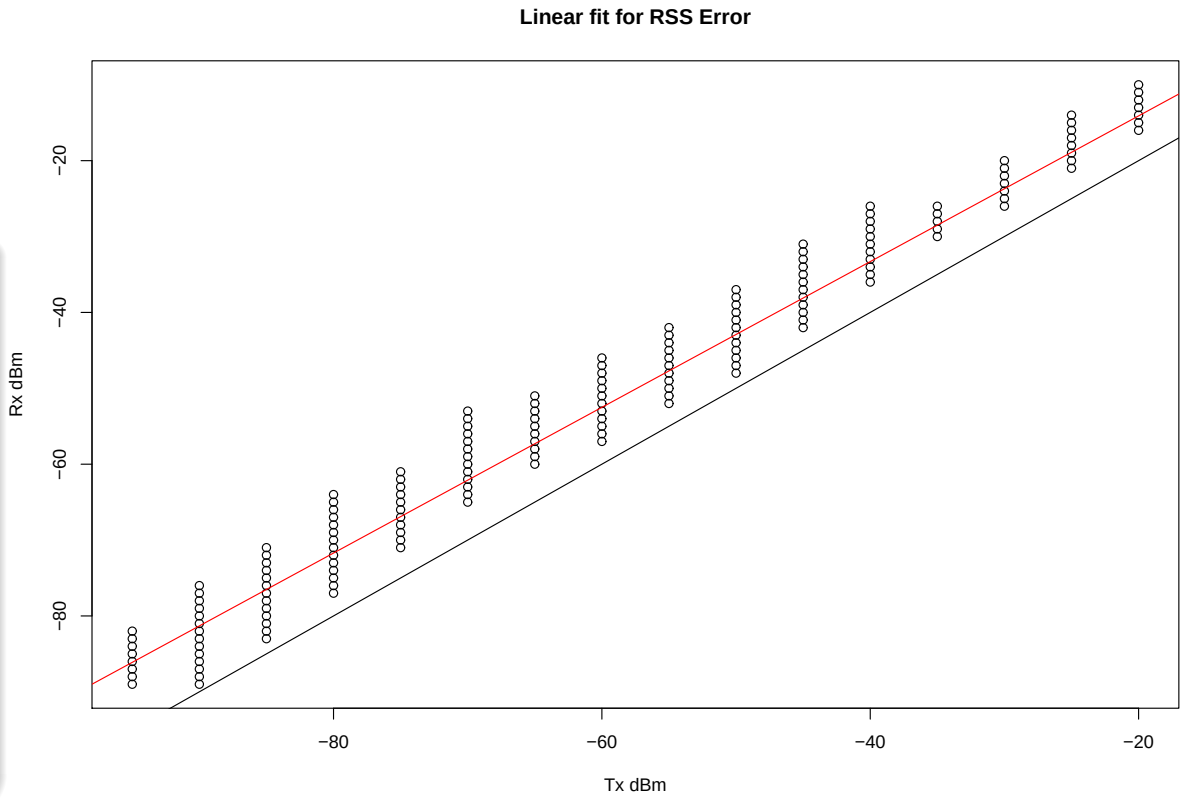
Calibration and test quality equipment (Agilent E4438C, 89600S VSG and VSA) used for:

- Reference pattern
- Calibrating laptop measurements.

Measurement Processes [2/2]

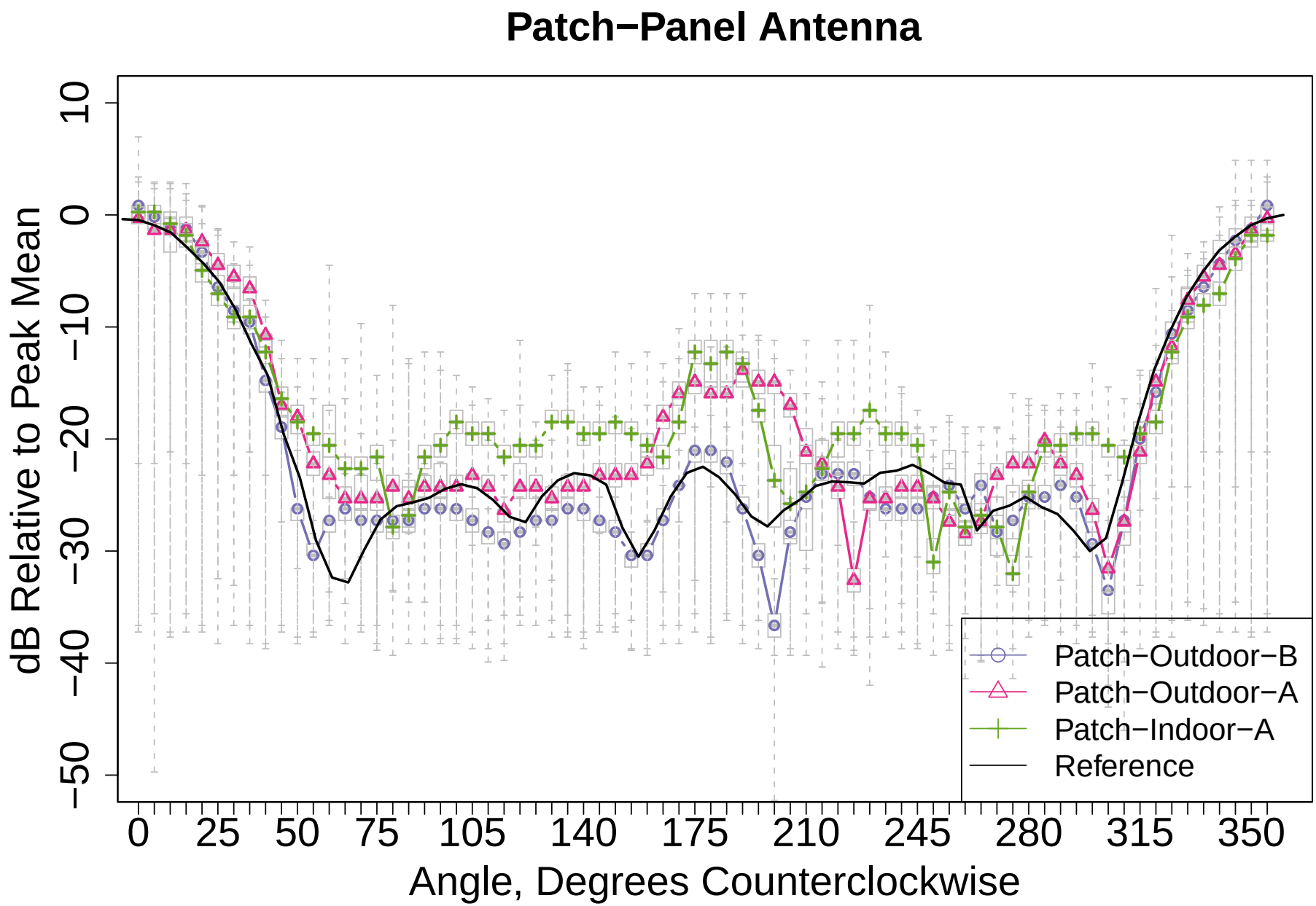
Laptop Measurements

- Dell laptops
- Atheros AR5213 radios
- Used for non-reference measurements.

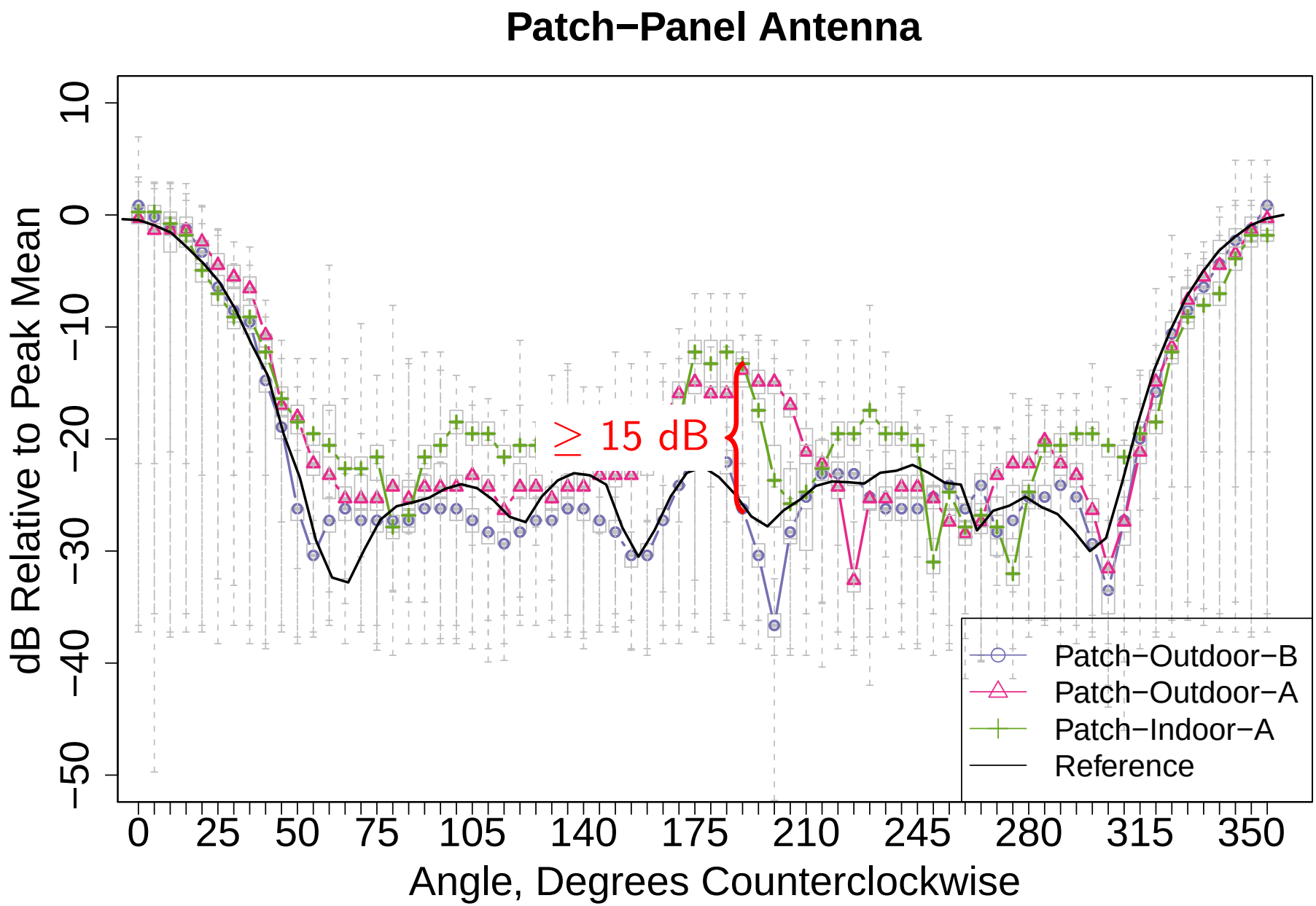


- Linear fit, slope ≈ 0.95
- Adjusted $R^2 = 0.989$

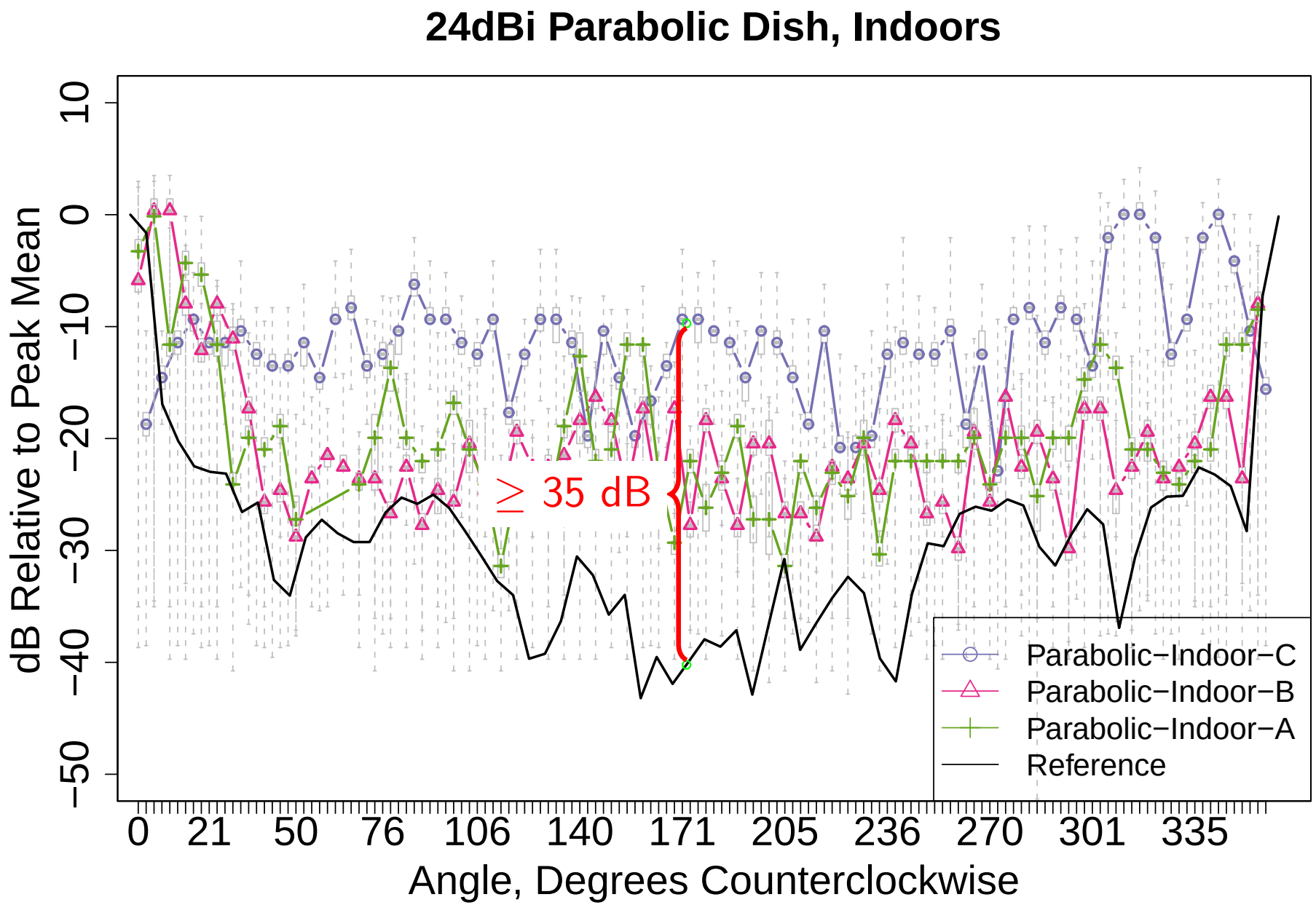
How Bad is it?


Patch−Panel Antenna
dB Relative to Peak Mean
10
0
−10
−20
−30
−40
−50
0
25
50
75
105
140
175
210
245
280
315
350
Angle, Degrees Counterclockwise
Patch−Outdoor−B
Patch−Outdoor−A
Patch−Indoor−A
Reference

How Bad is it?


Patch−Panel Antenna
dB Relative to Peak Mean
10
0
−10
−20
−30
−40
−50
≥ 15 dB
Patch−Outdoor−B
Patch−Outdoor−A
Patch−Indoor−A
Reference
0
25
50
75
105
140
175
210
245
280
315
350
Angle, Degrees Counterclockwise

How Bad Is It?


24dBi Parabolic Dish, Indoors
dB Relative to Peak Mean
10
0
−10
−20
−30
−40
−50
≥ 35 dB
0
21
50
76
106
140
171
205
236
270
301
335
Angle, Degrees Counterclockwise
Parabolic−Indoor−C
Parabolic−Indoor−B
Parabolic−Indoor−A
Reference

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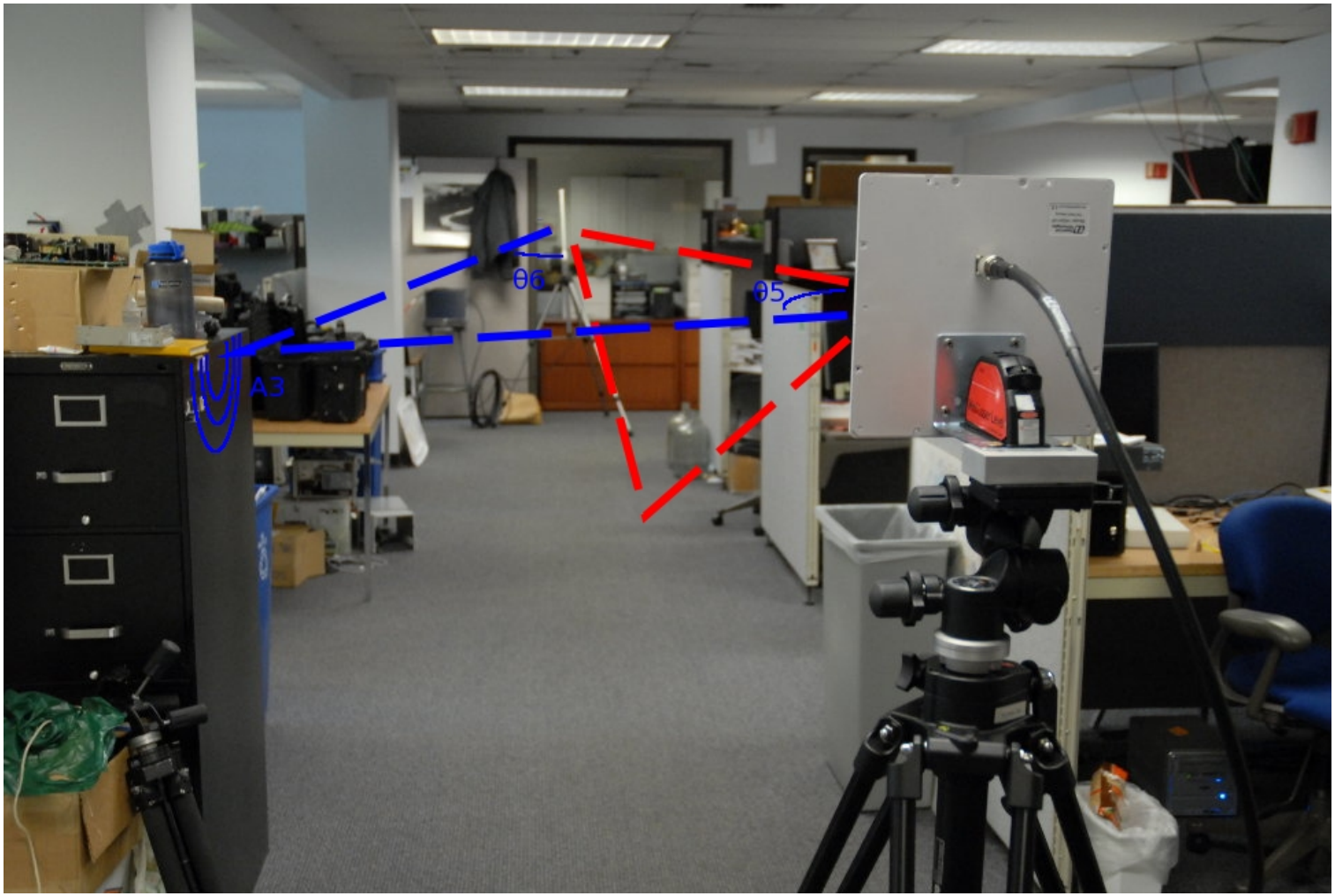
Radio Ray Tracing

$$P_{rx} = P_{tx} \left| \left(f_a(\theta_1) f_b(\theta_2) d_1^{-2} \right) \right|$$

Radio Ray Tracing

$$P_{rx} = P_{tx} \left| \left(f_a(\theta_1) f_b(\theta_2) d_1^{-2} + f_a(\theta_3) f_b(\theta_4) d_2^{-2} A_2 \right) \right| \qquad \text{“two-ray”}$$

Radio Ray Tracing



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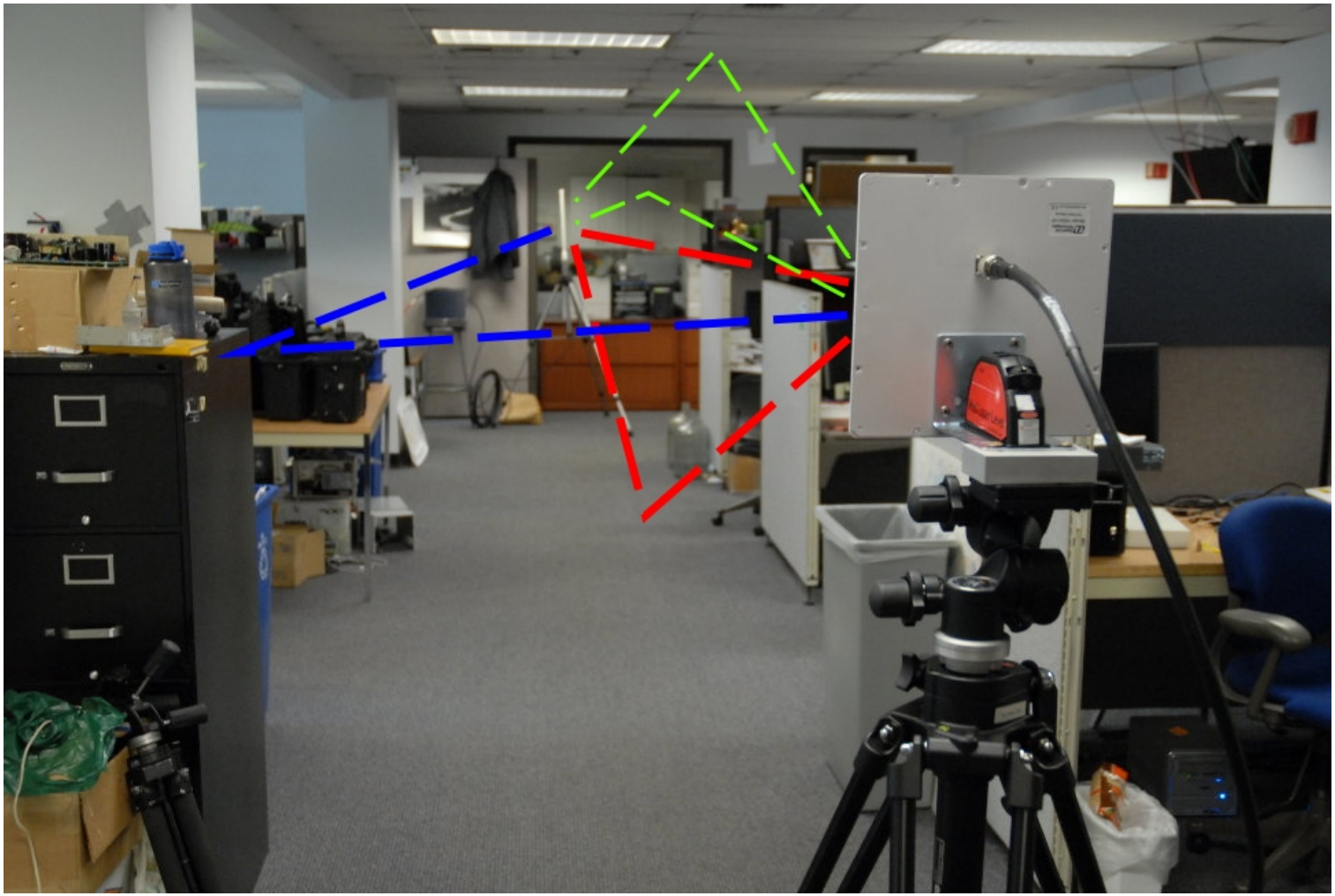
Radio Ray Tracing



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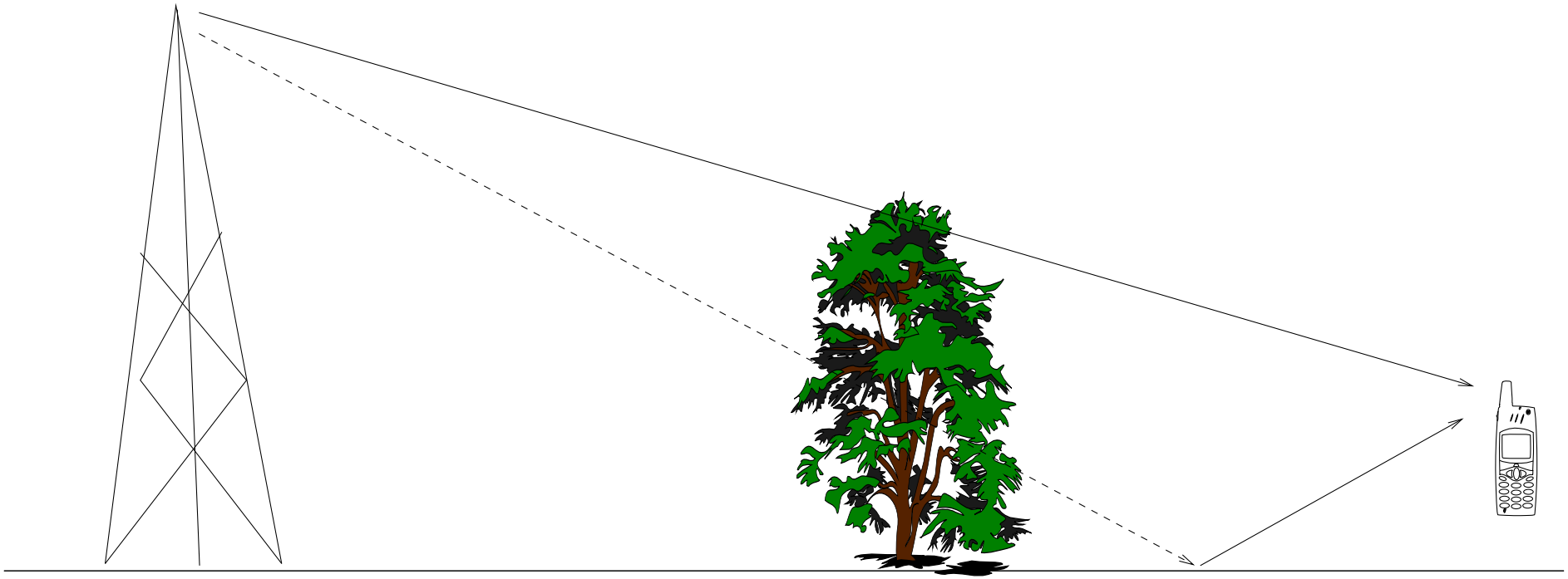
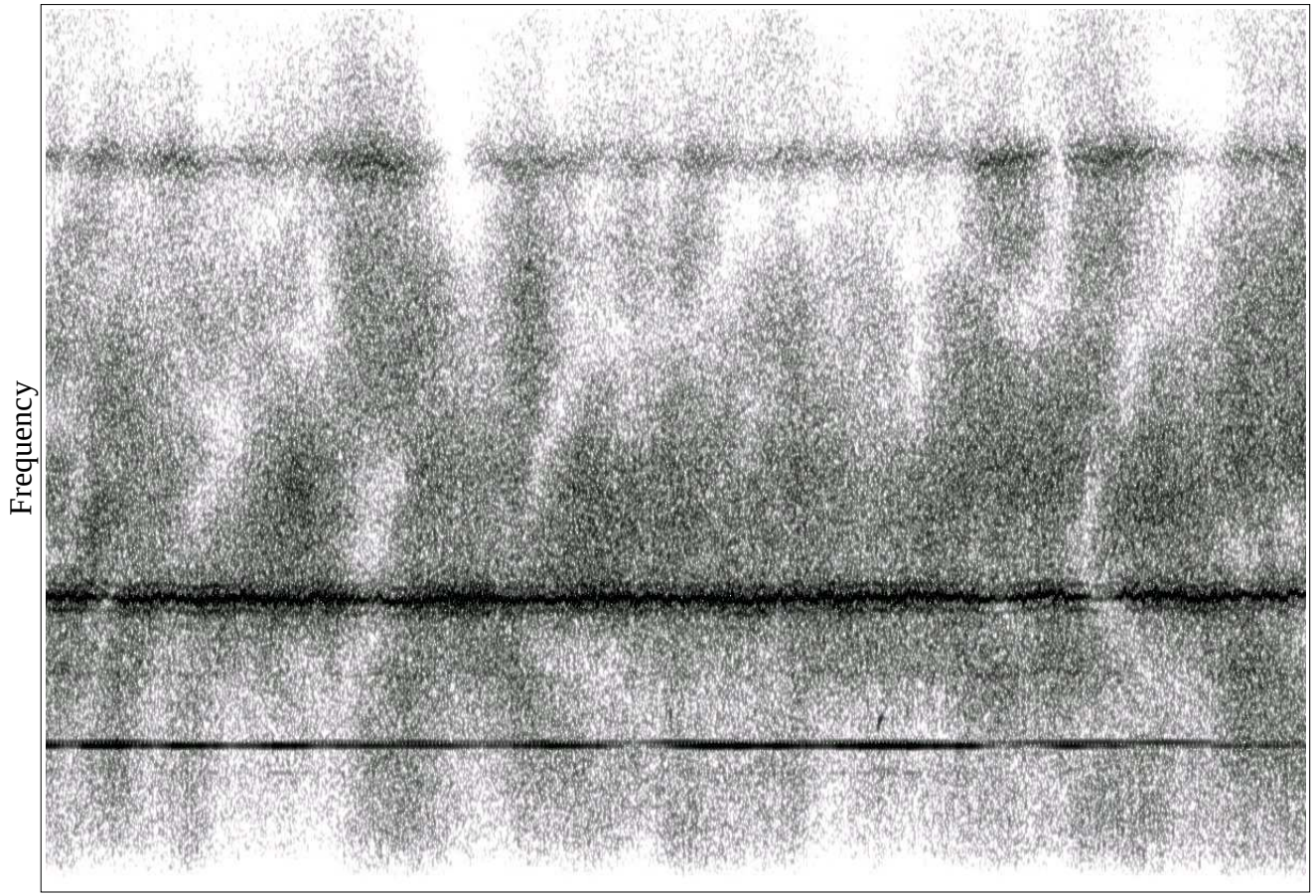
Path Loss



Path loss: Macro-scale function of position & terrain.

e.g. Free space, two-ray, HATA/COST231, ITU238, . . .

Fading

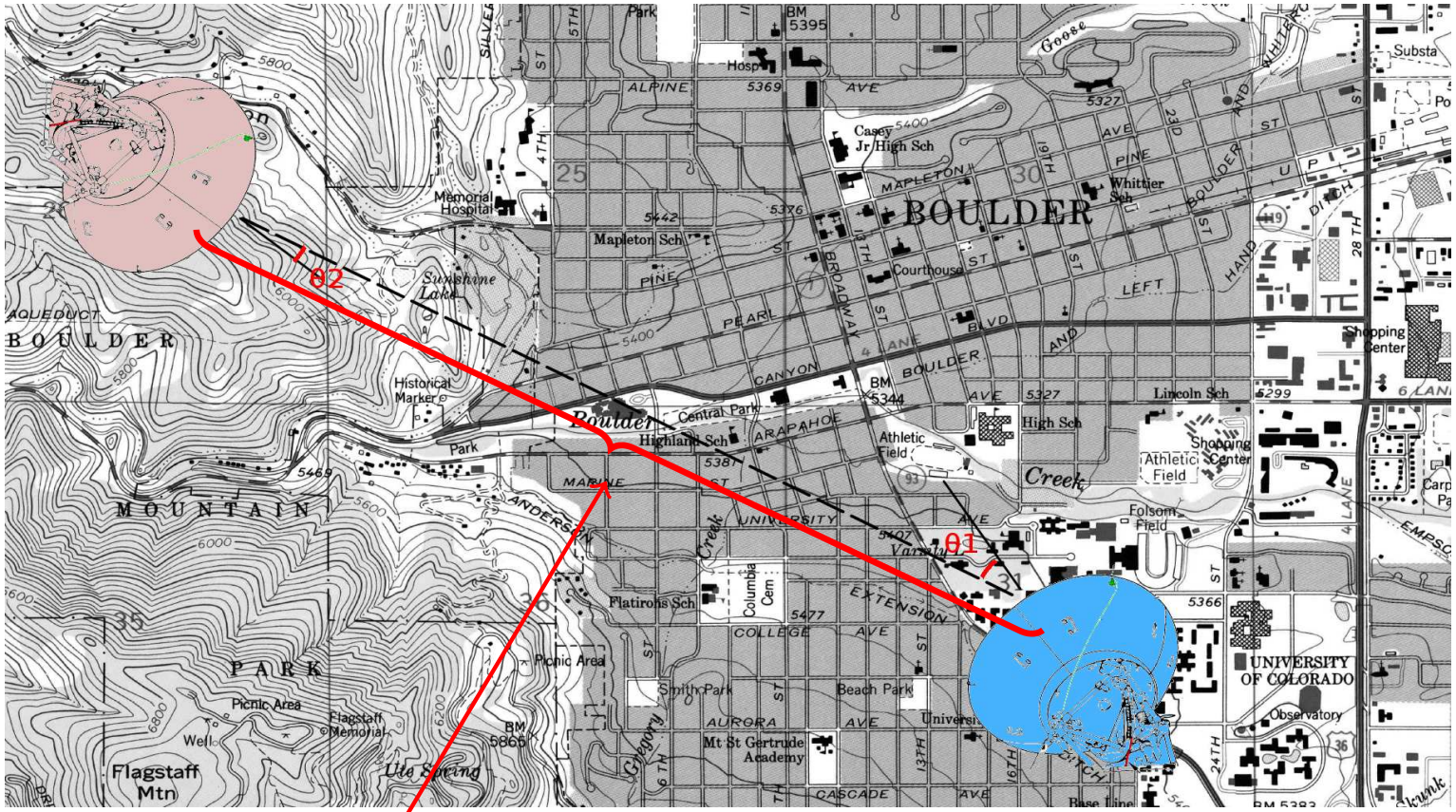


[Credit: Public domain image from Wikimedia commons]

Fading: Micro-scale function of *many* positions and velocities. Treated as function of time.

e.g. Rayleigh, Rician, Weibull, ...

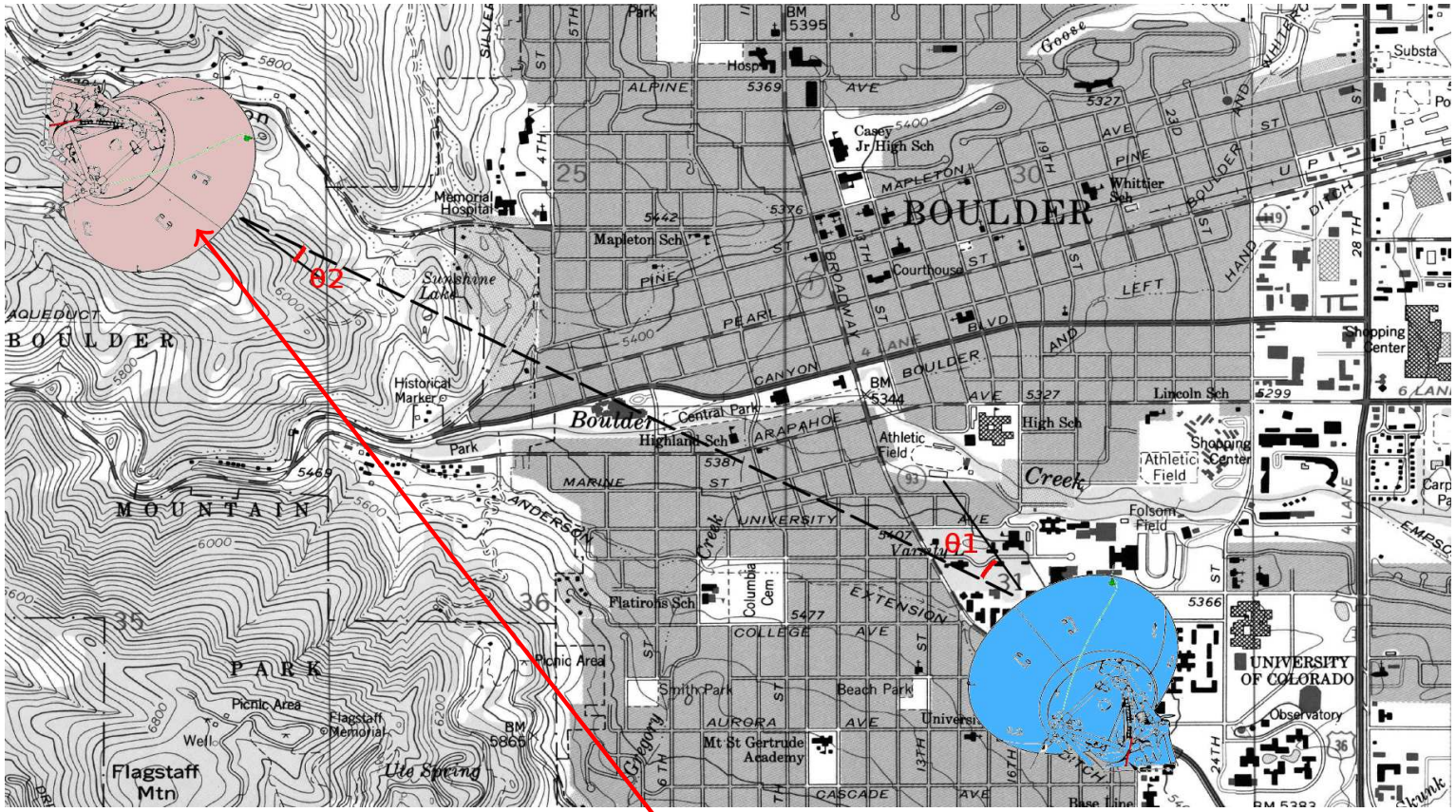
Directivity – Current Models



Fading & path loss Node a gain Node b gain

$$P_{rx} = P_{tx} * X * f_a(\theta_1) * f_b(\theta_2)$$

Directivity – Current Models



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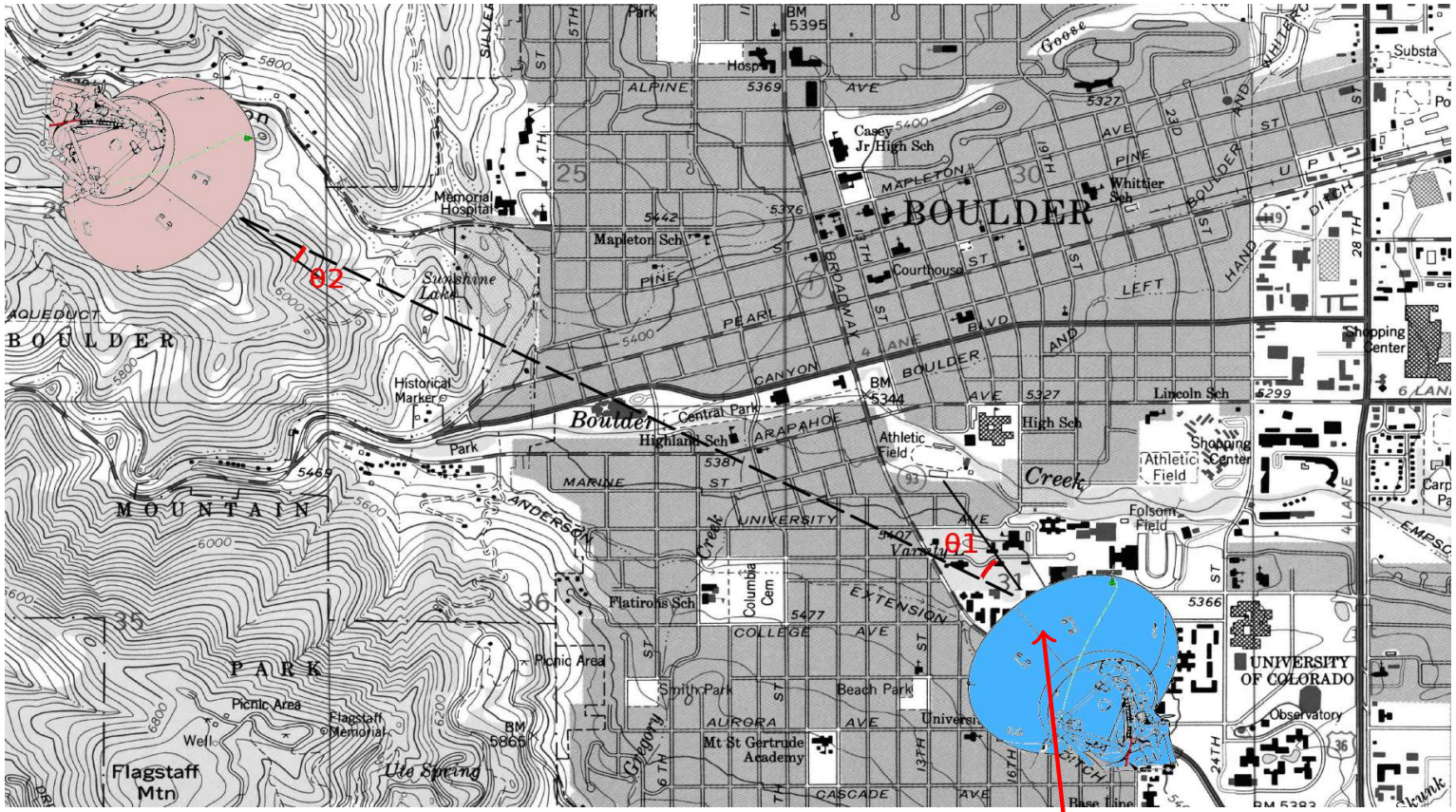

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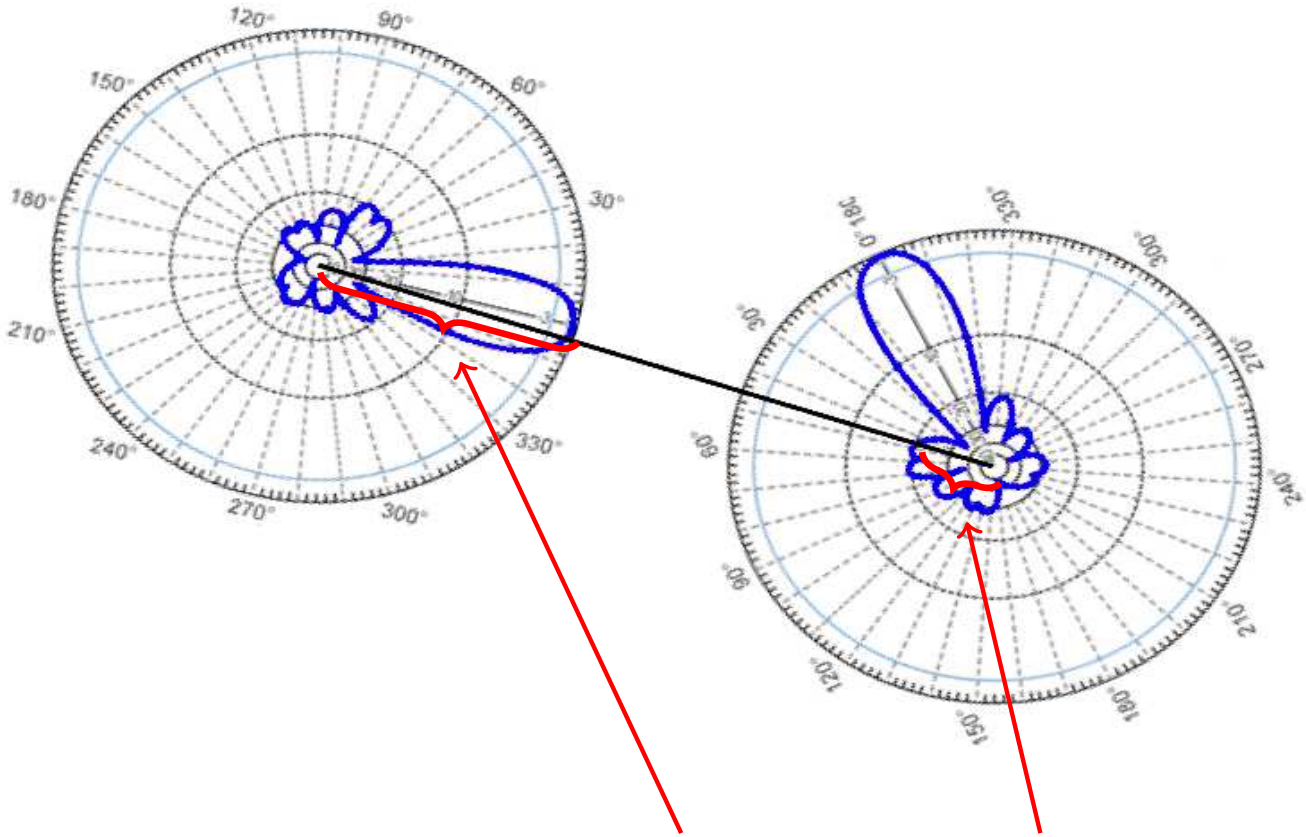

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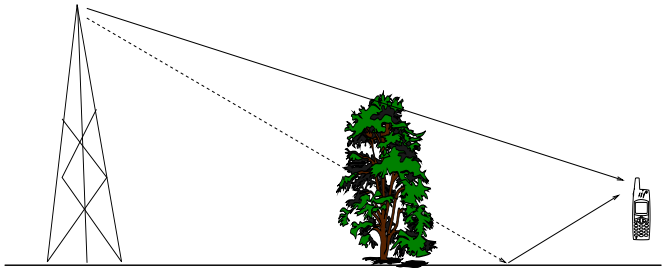
Directivity – What's Missing?



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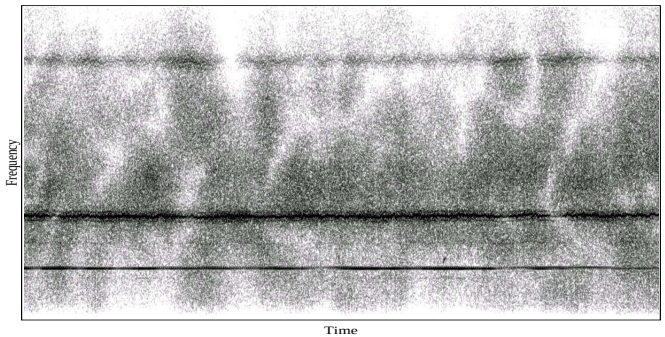

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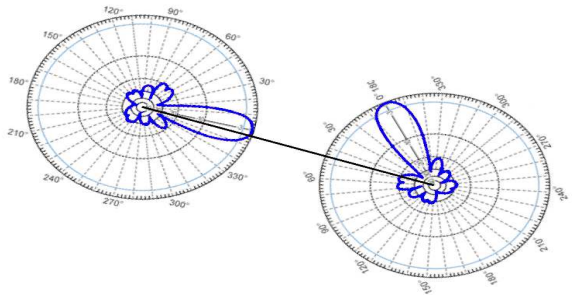


= ?

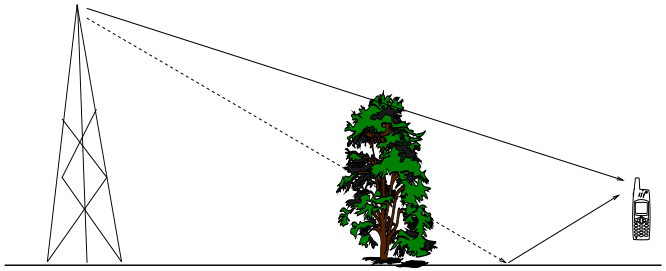
$$\underbrace{\text{Some f(position)} * \text{Some f(time)}}$$

$$P_{rx} = P_{tx} * X * f_a(\theta_1) * f_b(\theta_2)$$

vs.

$$P_{rx} = P_{tx} * \left| \begin{pmatrix} f_a(\theta_1) * f_b(\theta_2) * d_1^{-2} + \\ f_a(\theta_3) * f_b(\theta_4) * d_2^{-2} * A_2 + \\ f_a(\theta_5) * f_b(\theta_6) * d_3^{-2} * A_3 + \\ \cdots \end{pmatrix} \right|$$

Directivity – What's Missing?



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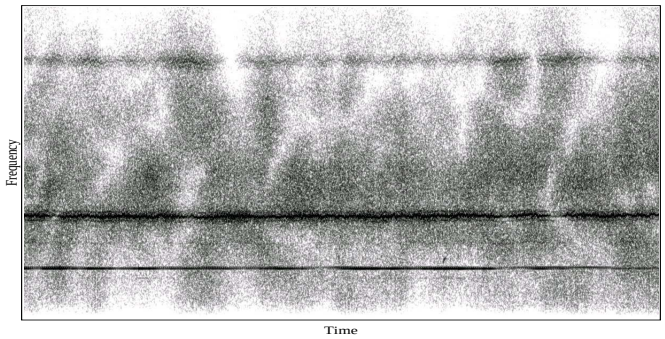

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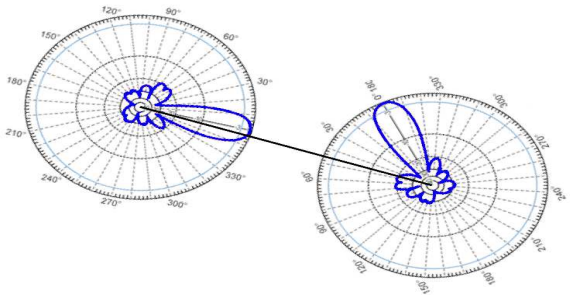

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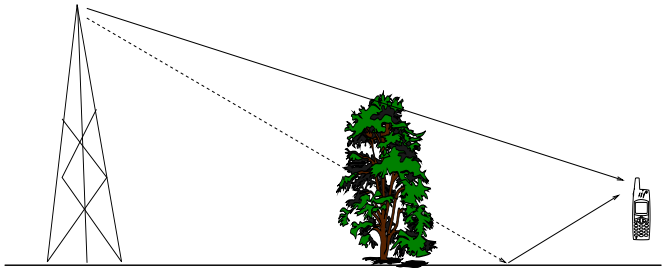

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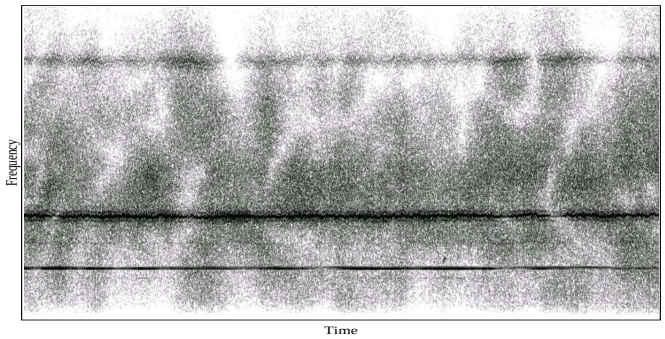

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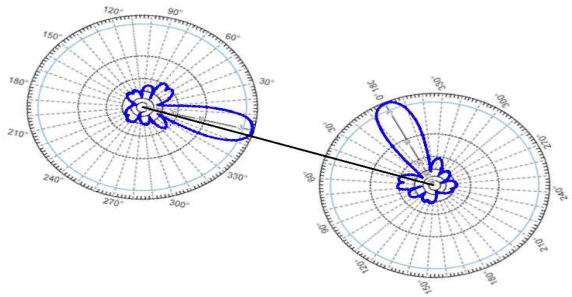

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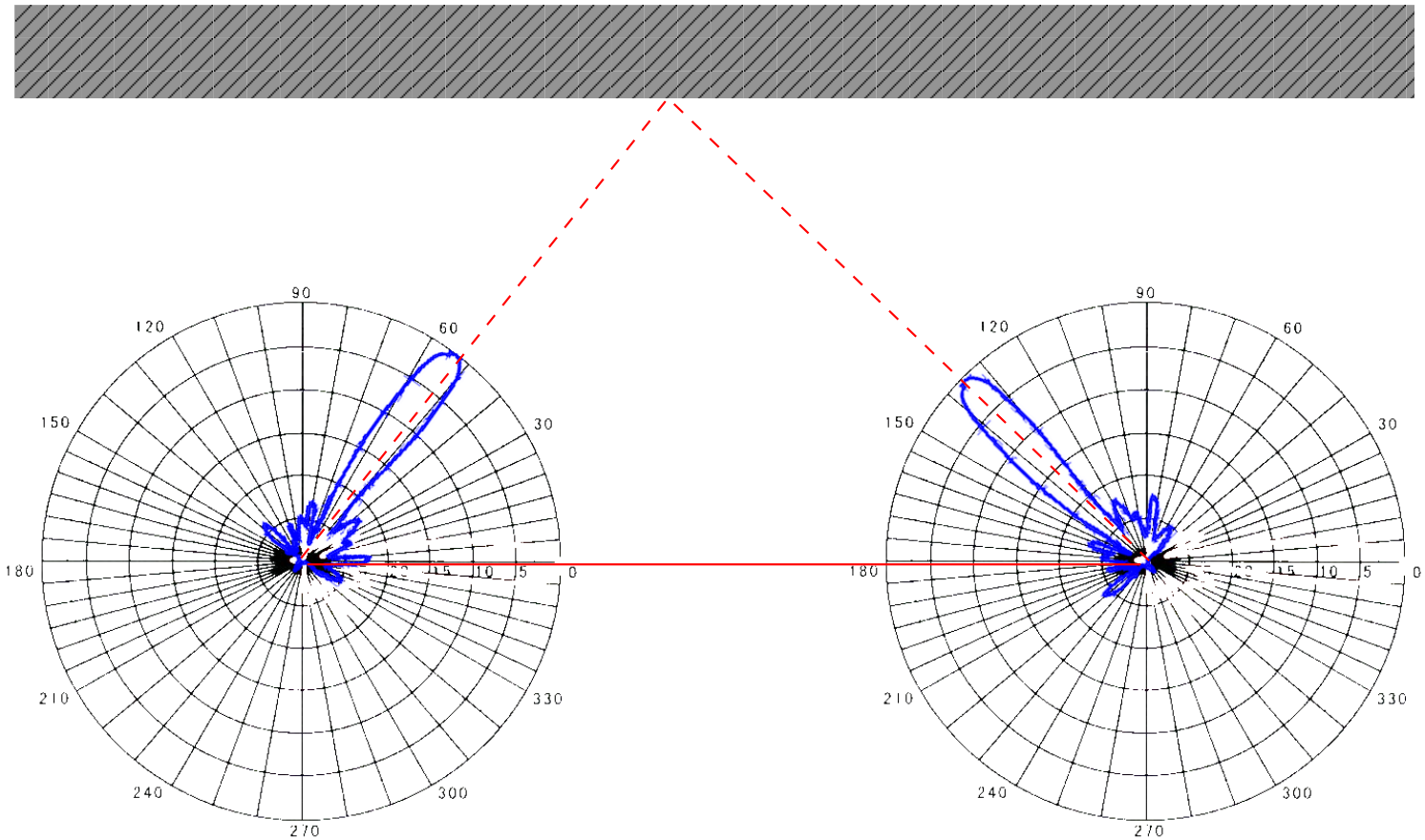
Antenna gain in "off" directions is ignored!

An Obvious Problem



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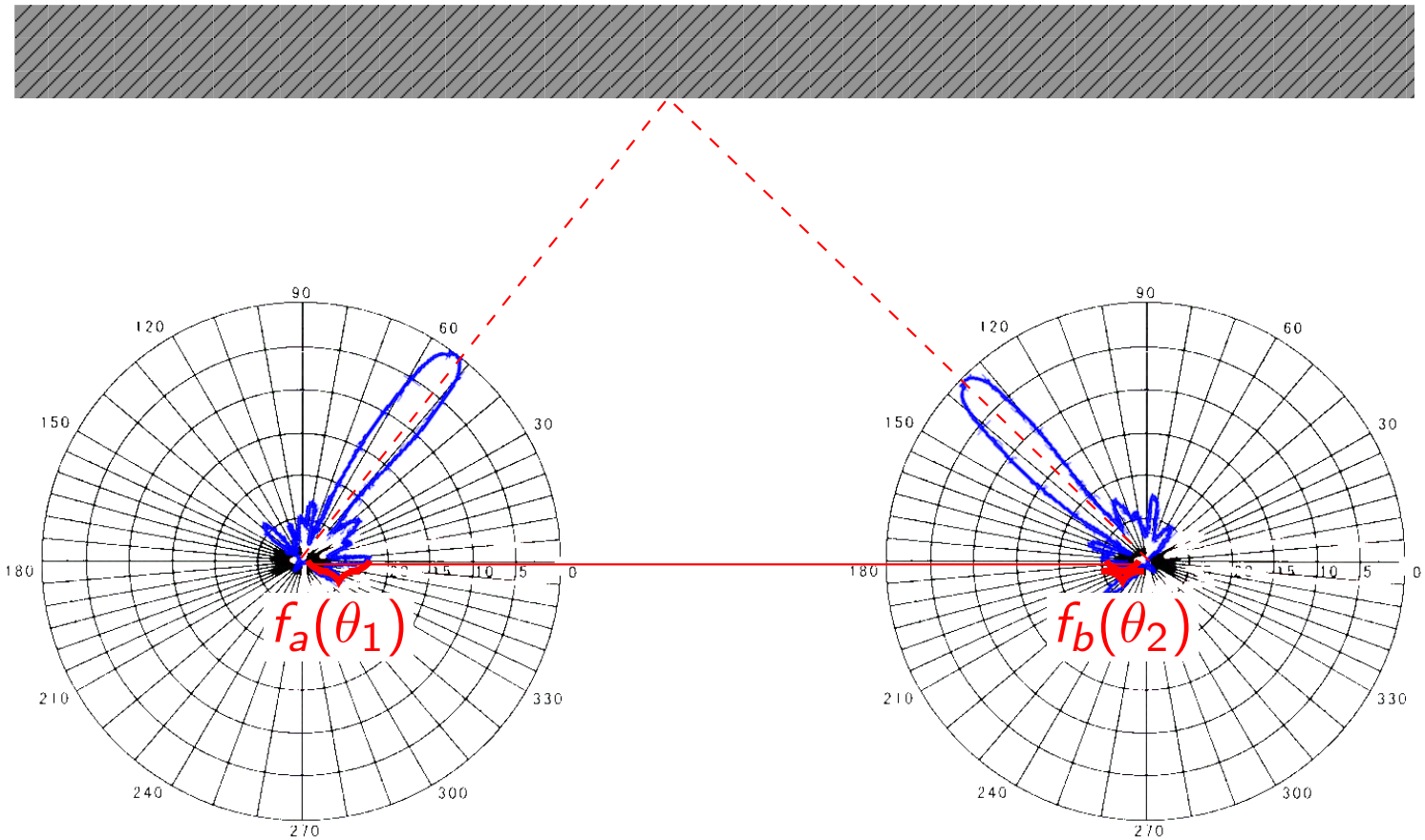

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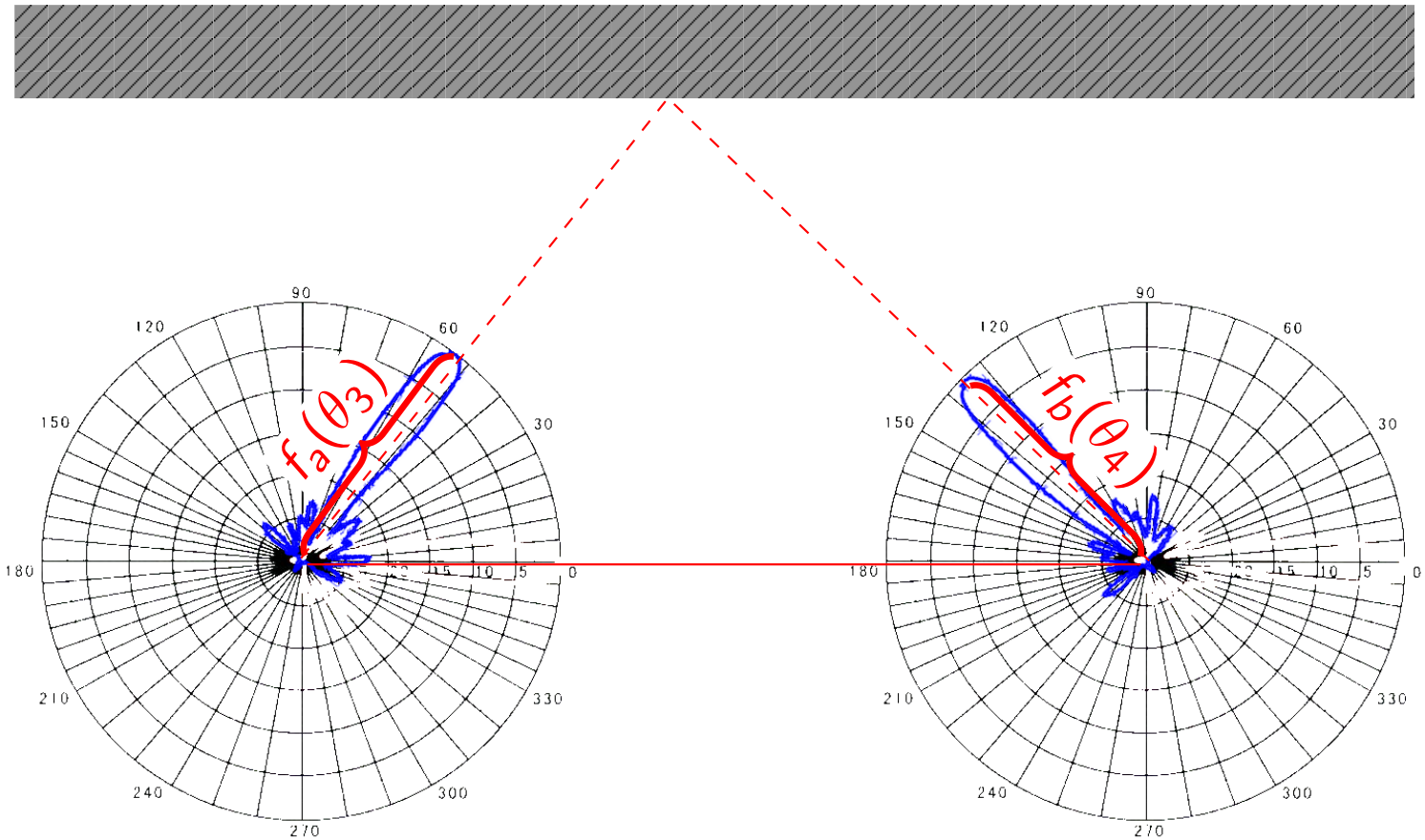

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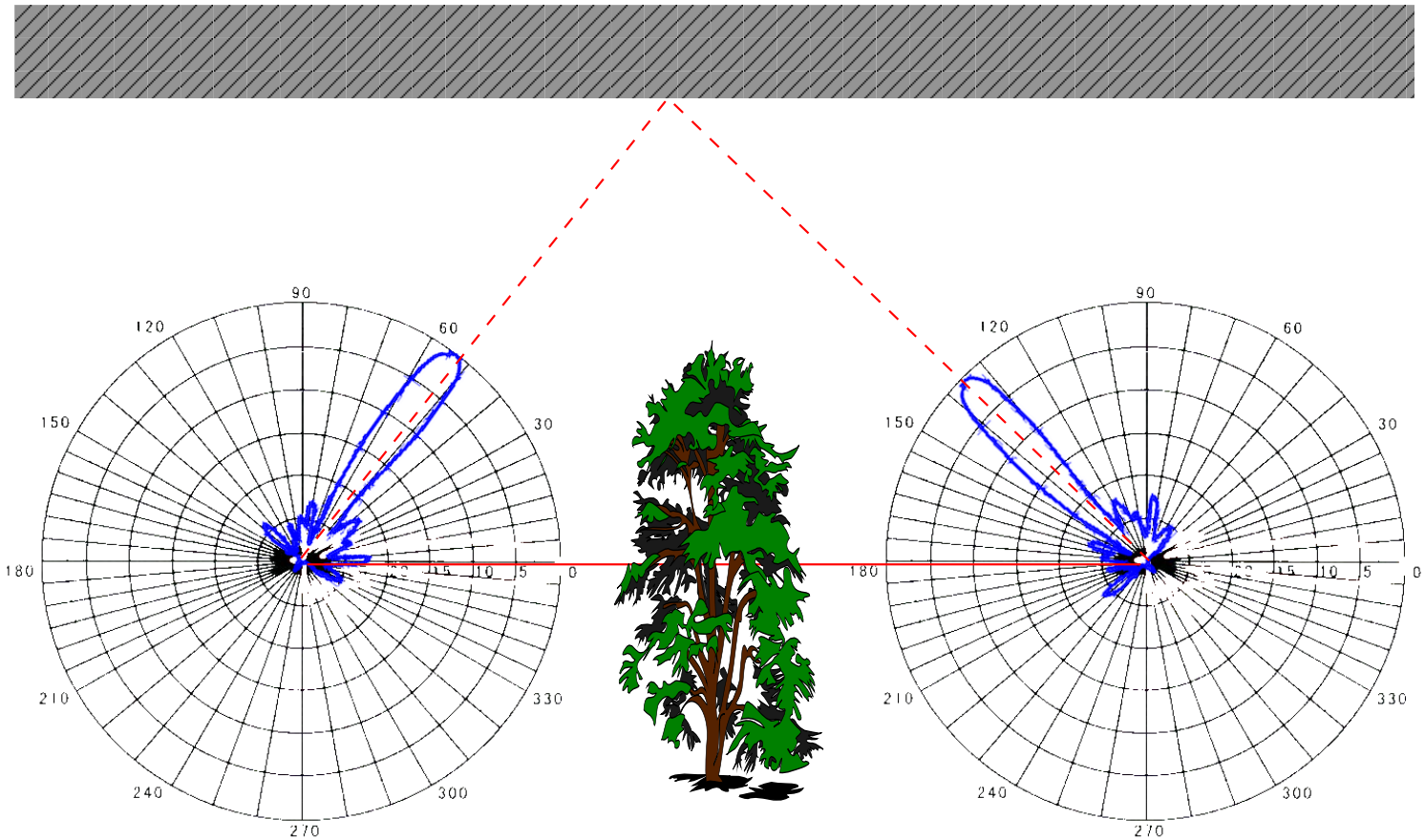

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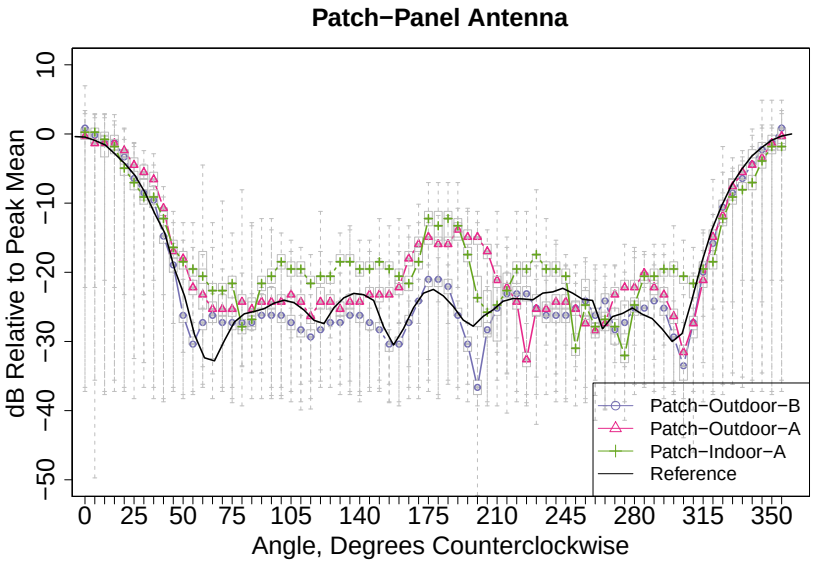
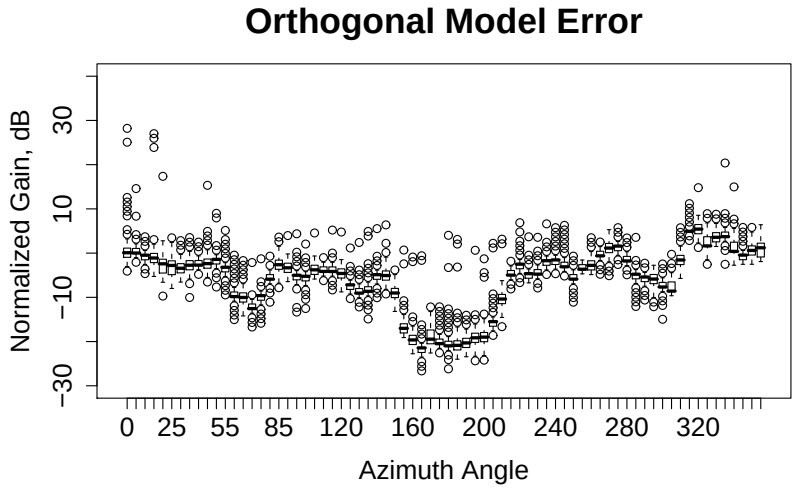
Environment Fitting

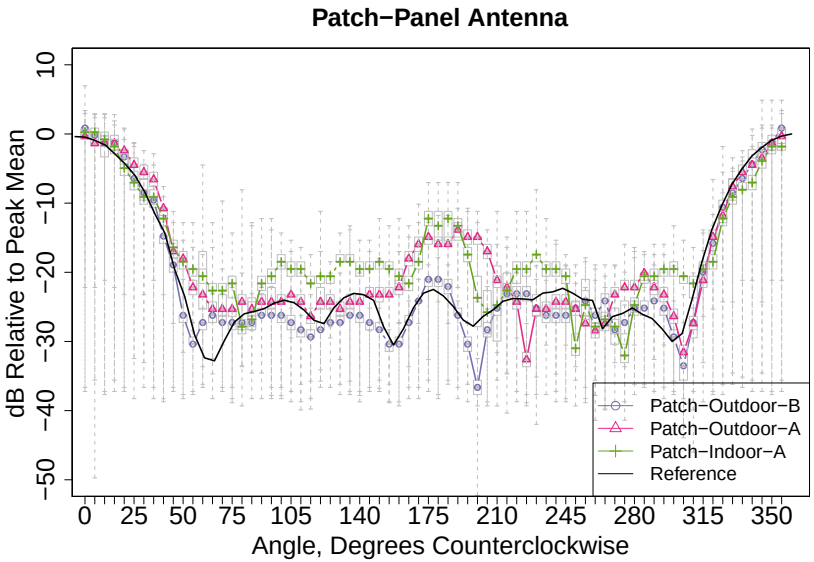


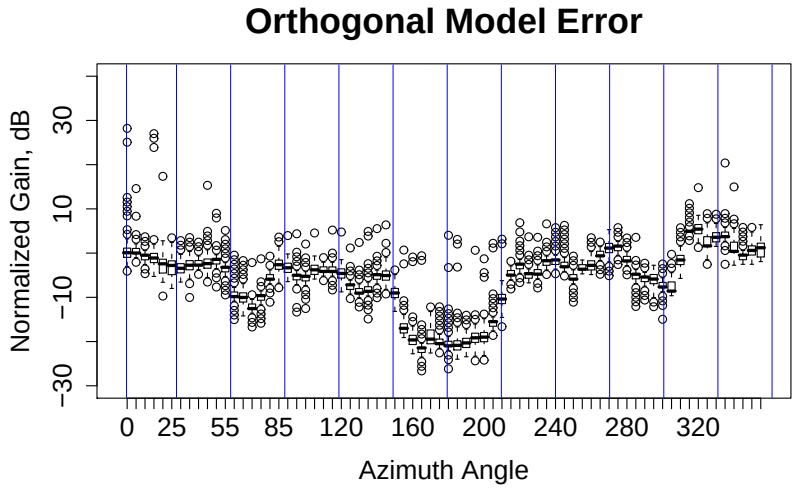


"Environment" = "Error"

- Error is correlated with angle
- Fit existing model error
  - Bin by angle
  - Find regression fit
- Characterizes specific link, antenna, environment.

Environment Fitting





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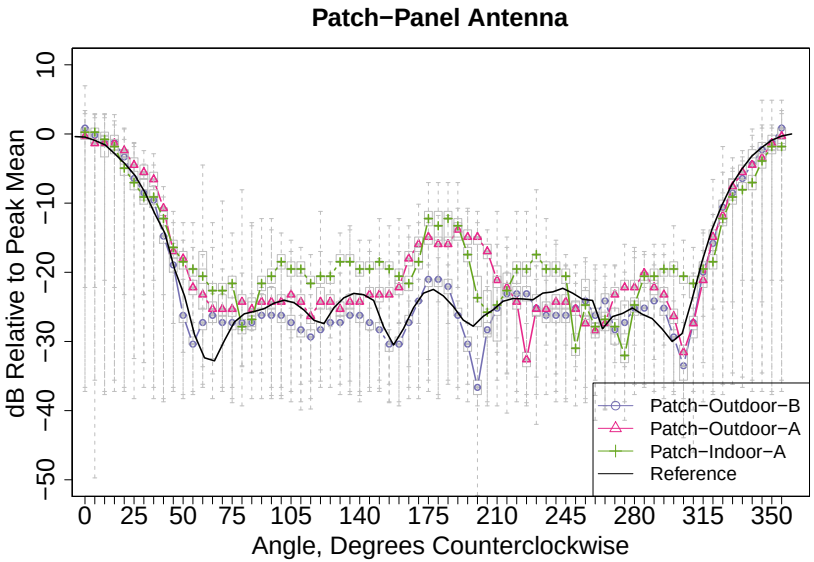

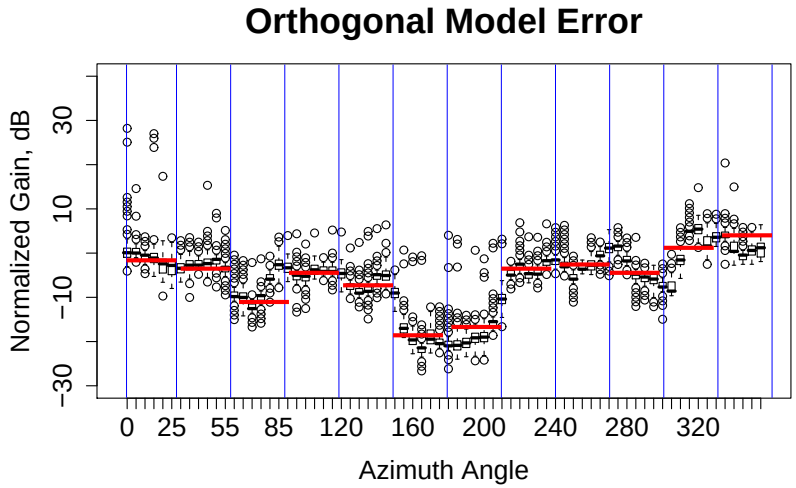

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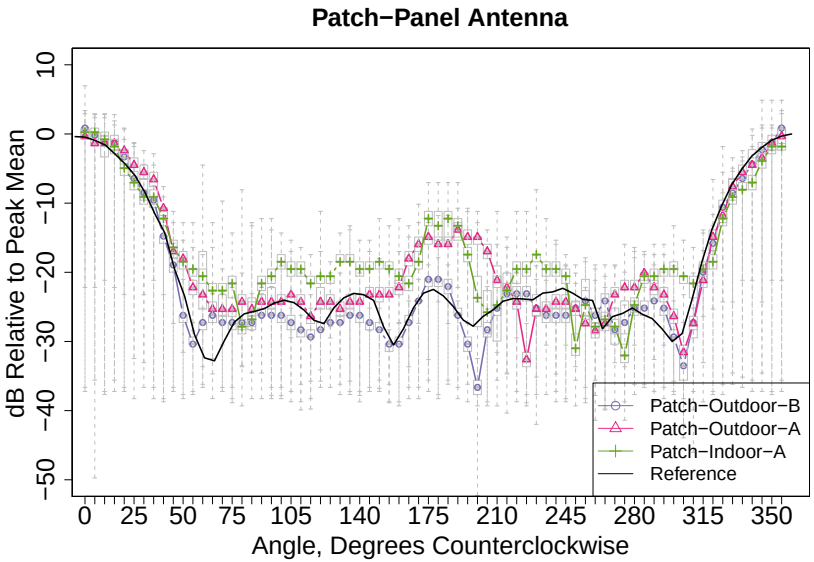

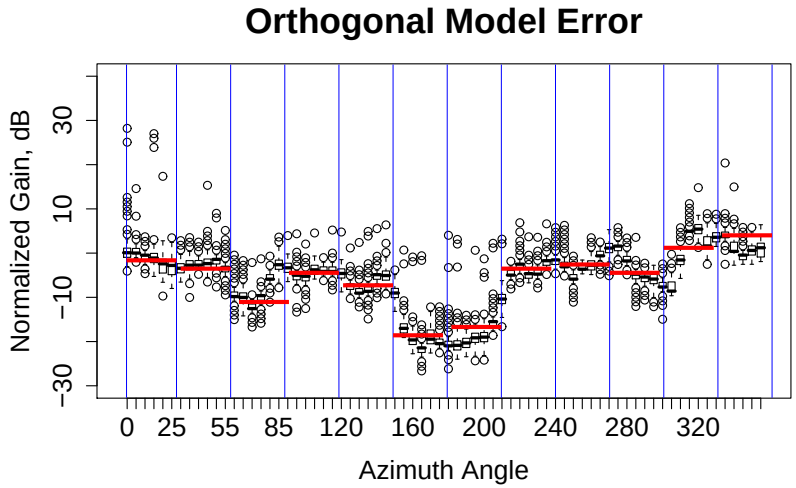

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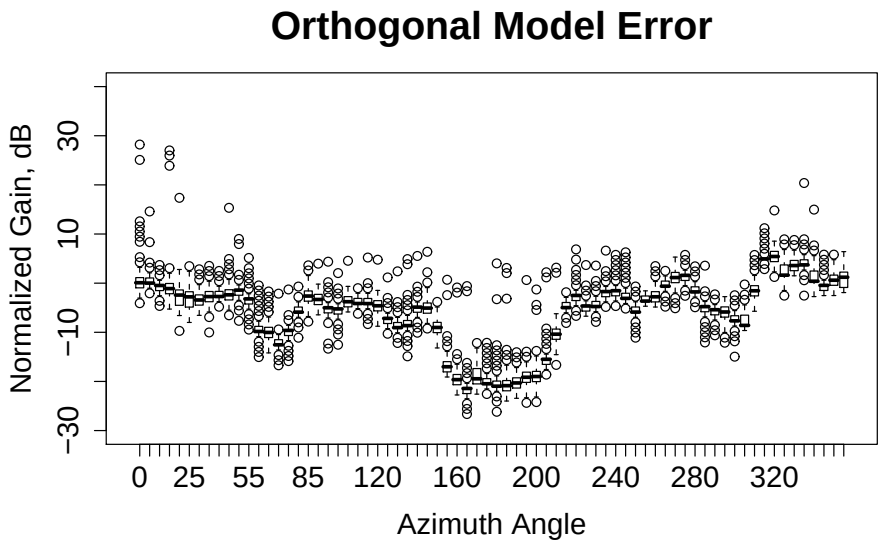
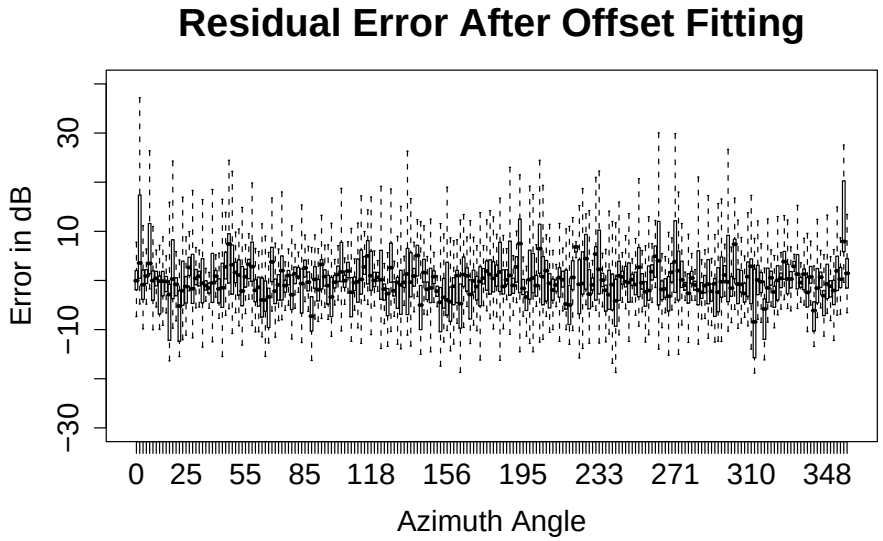
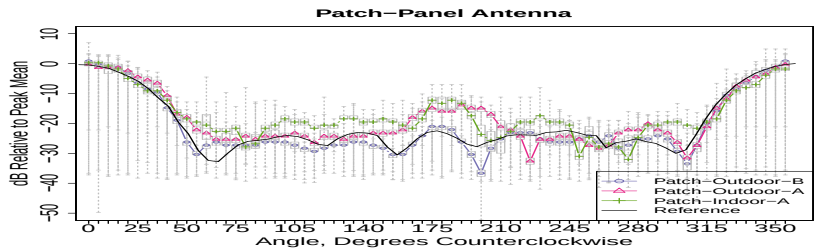
Error Comparison

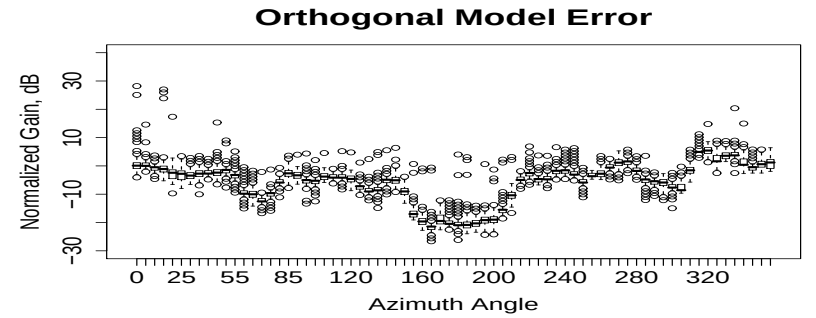


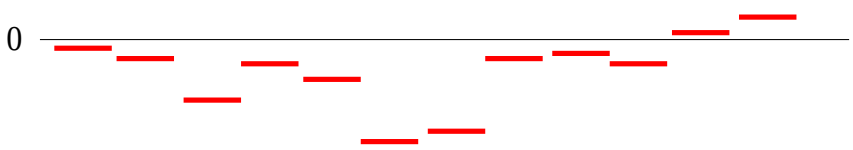


Types of Environments

Environment = set of offsets







e.g. {-1,-2,-5,-2,$\cdots$}

Group of environments = distribution of offsets

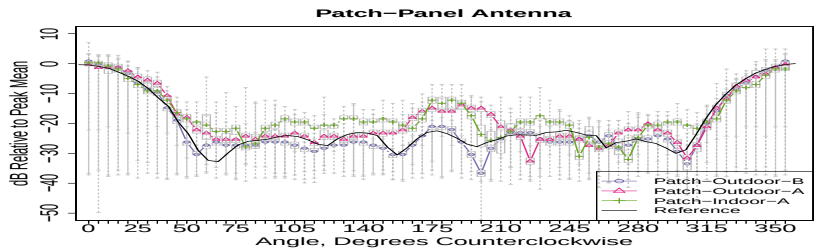
Offset ANOVA

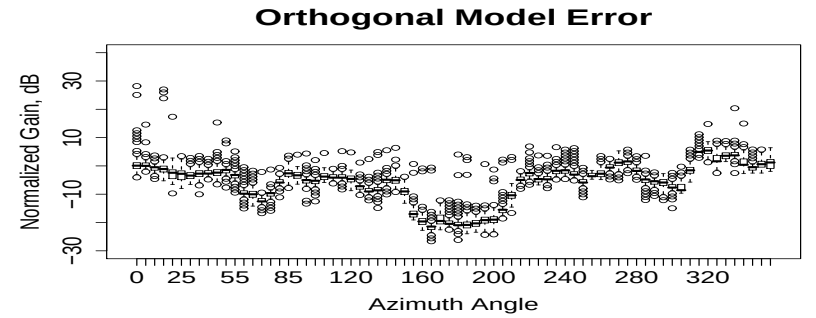
Variation is predicted by:

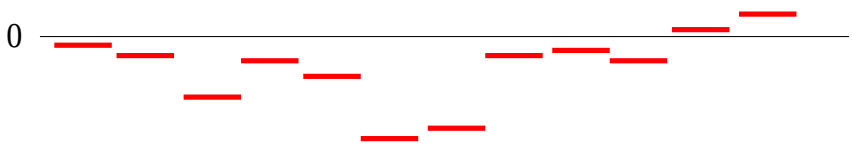
- "Type" of environment
- Antenna gain $f(\theta_k)$
- Observation point (negligible)

Types of Environments

Environment = set of offsets







e.g. {-1,-2,-5,-2,$\cdots$}

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- Observation point (negligible)

Therefore

(Type, antenna gain) $\Rightarrow$ offset distribution

Environment Parameters

Antenna a, bin k

Arc of azimuth centered at θ_k. Fitted offset is Off_k

$$\begin{aligned} \mathrm{E}[Off_k] &= f_a(\theta_k) * \text{gain coefficient} \\ Off_k &\sim \mathrm{Nor}(\mathrm{E}[Off_k], \sigma(\text{offset})) \\ \text{Signal} &\sim \mathrm{Nor}(Off_k, \sigma(\text{signal})) \end{aligned}$$

Environment Parameters

Antenna a, bin k

Arc of azimuth centered at θ_k. Fitted offset is Off_k

$$\mathrm{E}[Off_k] = f_a(\theta_k) * \text{gain coefficient}$$
$$Off_k \sim \mathrm{Nor}(\mathrm{E}[Off_k], \sigma(\text{offset}))$$
$$\text{Signal} \sim \mathrm{Nor}(Off_k, \sigma(\text{signal}))$$

Environment	K_{gain}	S_{off}	S_{ss}
Open Outdoor	0.01 - 0.04	1.326 - 2.675	2.68 - 3.75
Urban Outdoor	0.15 - 0.19	2.244 - 3.023	2.46 - 2.75
LOS Indoor	0.25 - 0.38	2.837 - 5.242	2.9 - 5.28
NLOS Indoor	0.67 - 0.70	3.17 - 3.566	3.67 - 6.69

Table: Summary of Regression Results: Gain-offset regression coefficient (K_{gain}), offset residual std. error (S_{off}), and signal strength residual std. error (S_{ss}).

Thank you

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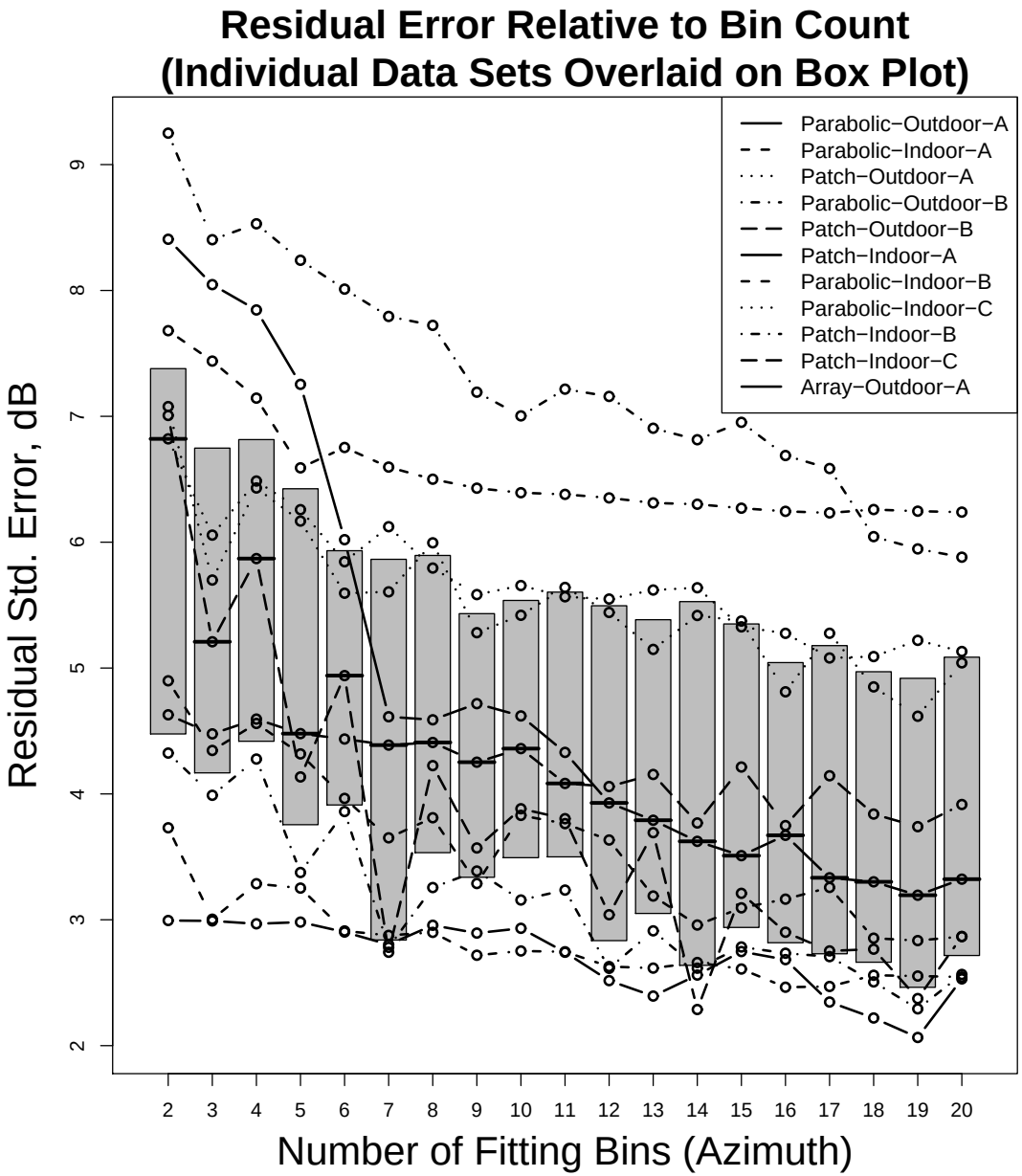
Measurements:
`http://www.crawdad.org/cu/antenna`

Simulation software (Qualnet 4.5.1 patch):
`http://systems.cs.colorado.edu/`

Bin Sizes


Residual Error Relative to Bin Count
(Individual Data Sets Overlaid on Box Plot)
Parabolic−Outdoor−A
Parabolic−Indoor−A
Patch−Outdoor−A
Parabolic−Outdoor−B
Patch−Outdoor−B
Patch−Indoor−A
Parabolic−Indoor−B
Parabolic−Indoor−C
Patch−Indoor−B
Patch−Indoor−C
Array−Outdoor−A
Residual Std. Error, dB
2
3
4
5
6
7
8
9
2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
Number of Fitting Bins (Azimuth)