Wind Turbine Scattering at HF
MIT LL Quick-look Outbrief

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Sponsor: Michael Aimone, OSD OUSD/AT&L

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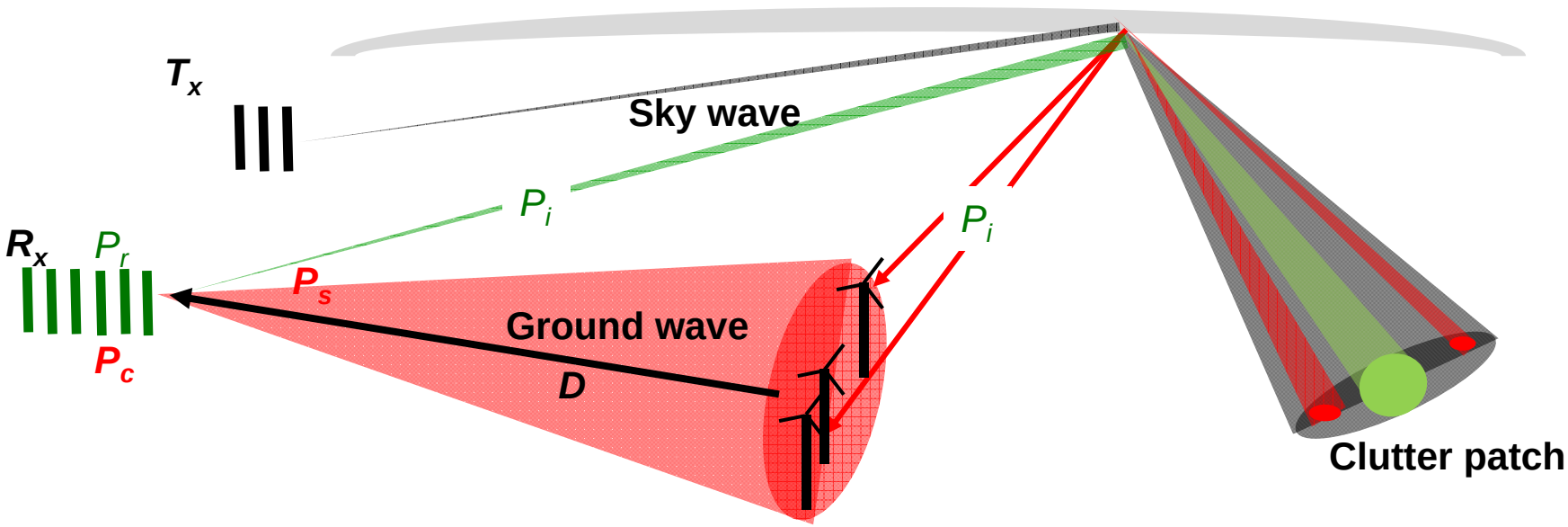
Outline

- Introduction
  - Bottom line up front
- Modeling approach
- Summary
- Backup and Additional Information

Bottom Line Up Front

- **Wind Turbine model developed**
  - **Based on the Numerical Electromagnetics Code (NEC) version 4.2 method of moments solution of the electric field integral equation for thin wires**
- **Model used with radar parameters to generate Doppler signatures of wind turbine modulated clutter**
- **Model used to estimate changes to standoff requirements based on wind direction**
- **A great deal of effort was expended attempting to validate all modeling efforts**
  - **Limited runs were performed**

Wind-Farm Clutter Interference



$$\left[\frac{P_c}{P_r}\right]_M = \left[\frac{P_c}{P_r}\right]_1 \left[\frac{T_x}{R_x}\,\textit{Beam shape}\right] \left[\begin{array}{c}\textit{Near field array focusing}\\ \textit{loss of M turbines}\end{array}\right]$$

Turbine-to-incident clutter level

Single turbines

Effective number of turbines

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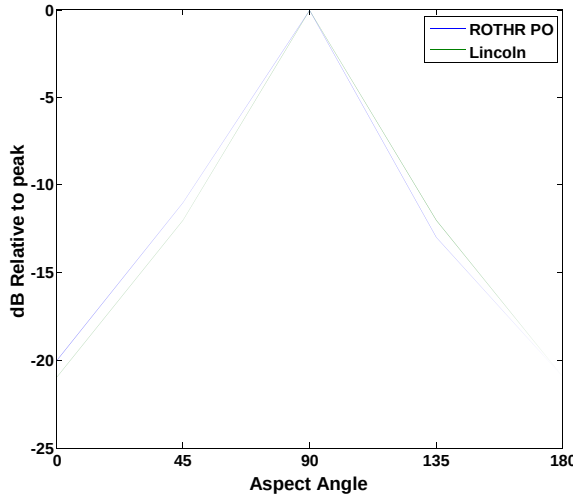
Standoff Range vs Turbine Aspect Angle

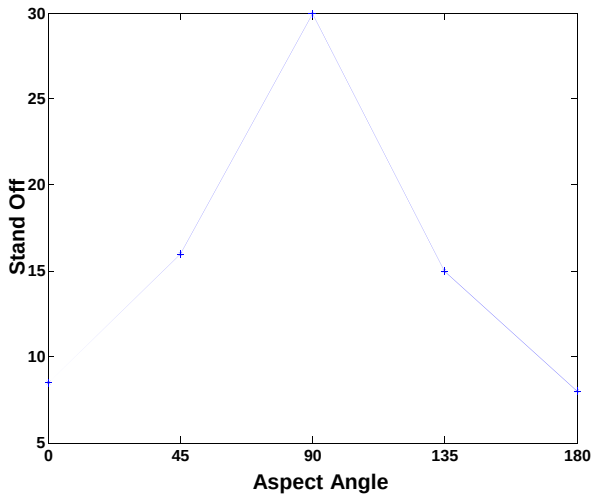
- **ROTHR[1] and Lincoln Laboratory simulations show the same dependence on Turbine Aspect Angle (i.e., wind direction)**
  - **Up to 20 dB less interference for broadside aspect vs end-on aspect**

Interference vs Aspect Angle for ROTHR and Lincoln Models



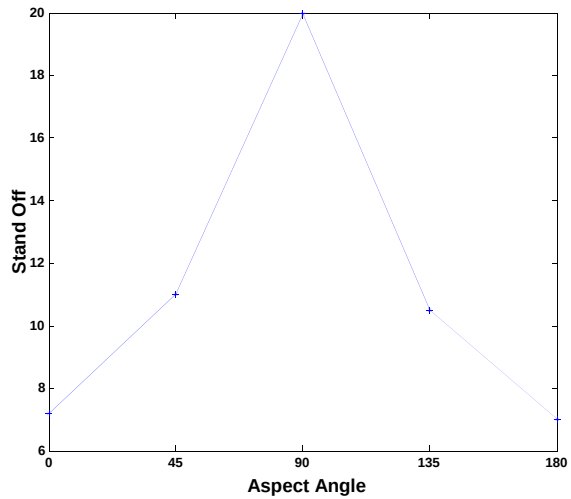
N NW/SE E/W SW/NE S
Wind Direction

Approximate Range of Standoff Values for 30 km Minimum



N NW/SE E/W SW/NE S
Wind Direction

Approximate Range of Standoff Values for 20 km Minimum



N NW/SE E/W SW/NE S
Wind Direction

1, "Comprehensive Modeling Analysis for Stand-Off Requirements of Wind Turbines from ROTHR Systems," RPO-TR-WF-0712-001, ROTHR Program Office, June 2012

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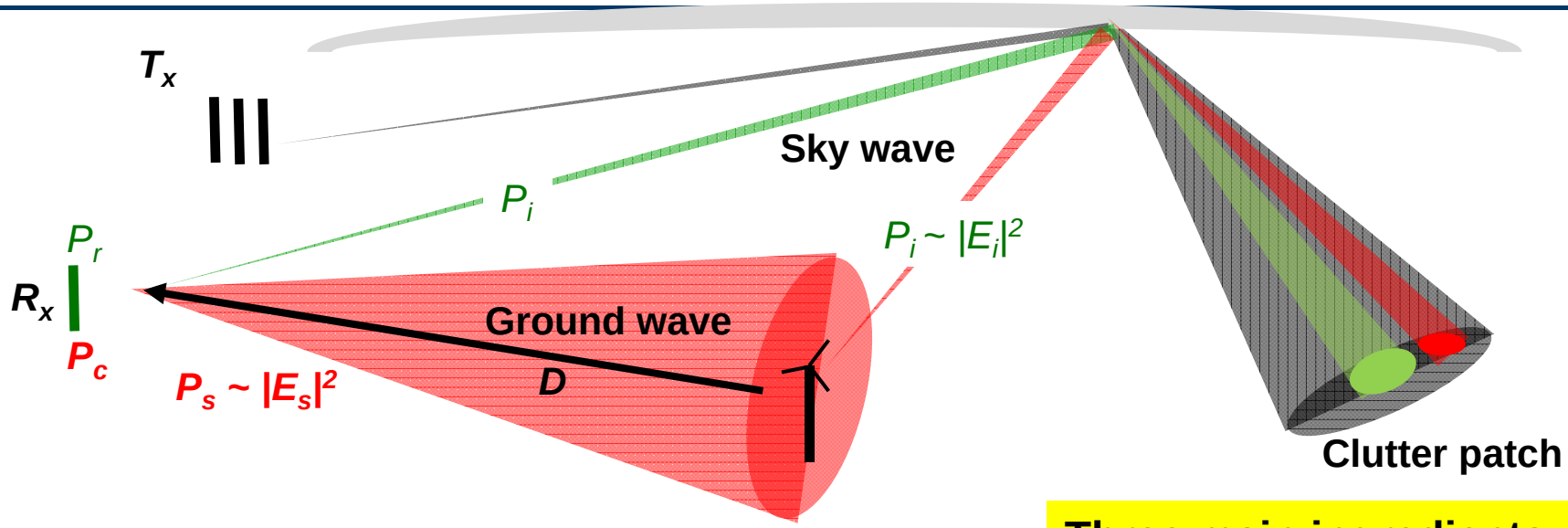
Single Wind Turbine Clutter Interference



$$\left[\frac{P_c}{P_r}\right]_1 = \left[\frac{G_c(0)}{G_r(\theta)}\right]\left|\frac{E_s(D)}{E_i}\right|^2$$

Three main ingredients:
1 Turbine scattering
2. Antenna response
3. Propagation

$G_r(\theta) = R_x$ *antenna response to incident wave* P_i *at* θ

$G_c(0) = R_x$ *antenna response to ground wave* P_s *at zero elevation*

$$\left|\frac{E_s(D)}{E_i}\right|^2 = \left[\frac{\textit{Scattered field power density } P_s \textit{ at } D}{\textit{Incident sky-wave power density } P_i}\right] = [\textit{Bistatic RCS},\ \sigma(\omega)]\left[\frac{F^2(D)}{4\pi D^2}\right]$$

Turbine RCS modulation spectrum

$$F^2(D) = \textit{Propagation loss factor}$$

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  - Antenna
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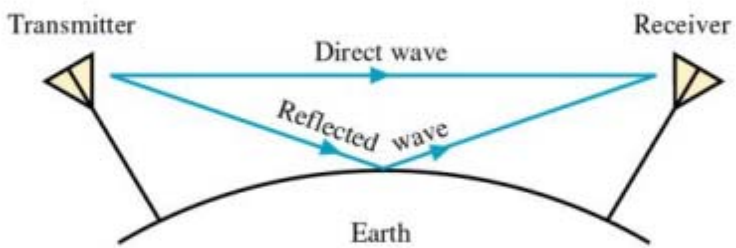
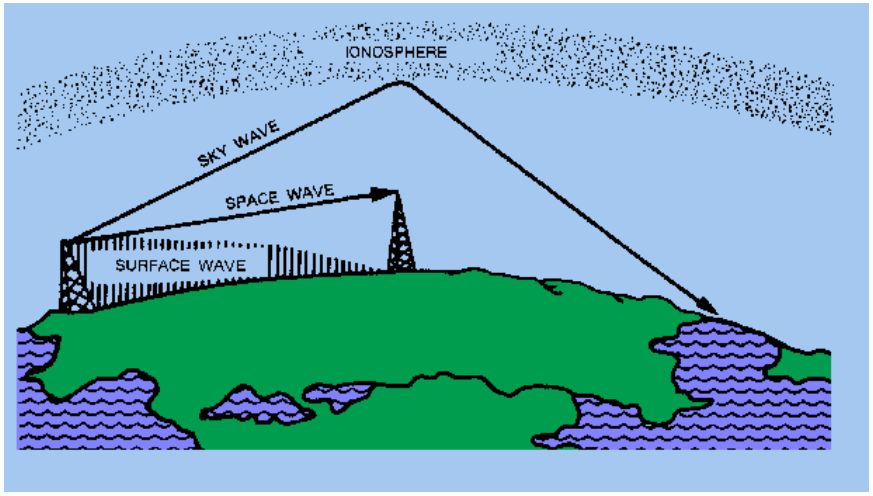
Three main ingredients:
1 Turbine scattering
2. Antenna response
3. Propagation

HF Propagation Near the Ground

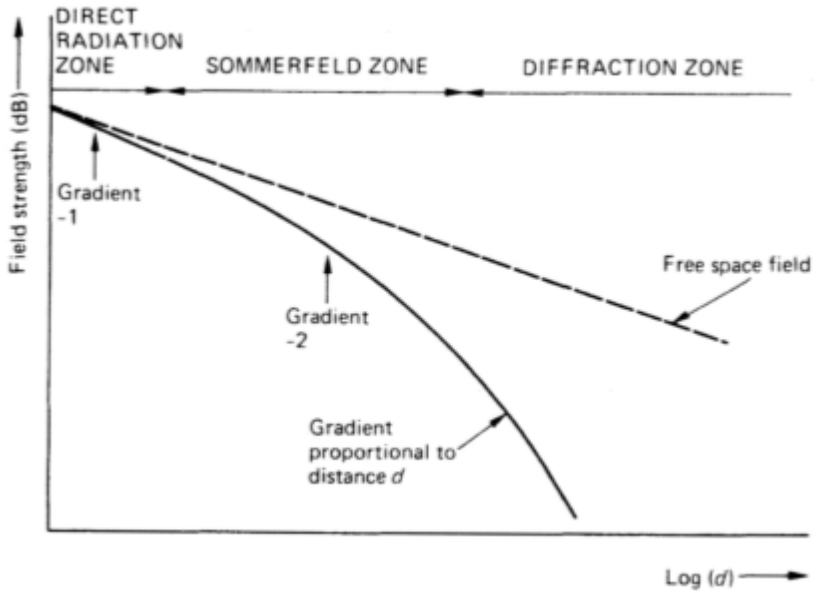
- **Propagation of radio waves near the ground is comprised of a sum of**
  - **Direct wave or space wave (often referred to as line-of-sight or LOS)**
  - **Reflected wave (generates multipath propagation when combined with direct wave)**
  - **Surface-attached wave (often referred to as ground wave)**
  - **Plus other terms (induction field and secondary effects)**



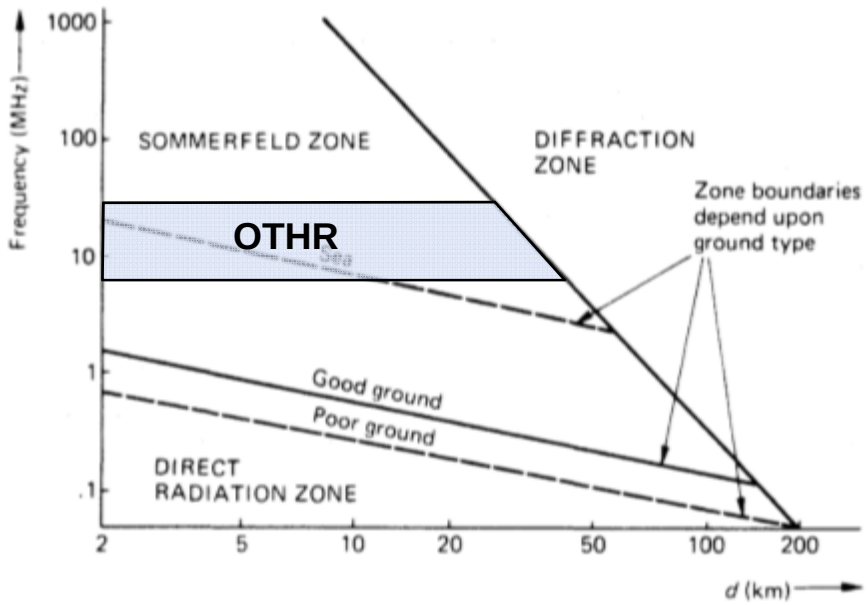


Propagation Zones for Antennas and Scatterers on the Ground

Propagation Zones



Boundary Locations



GRWAVE Handles 3 Propagation Zones: Space Wave (Direct), Sommerfeld, and Diffraction

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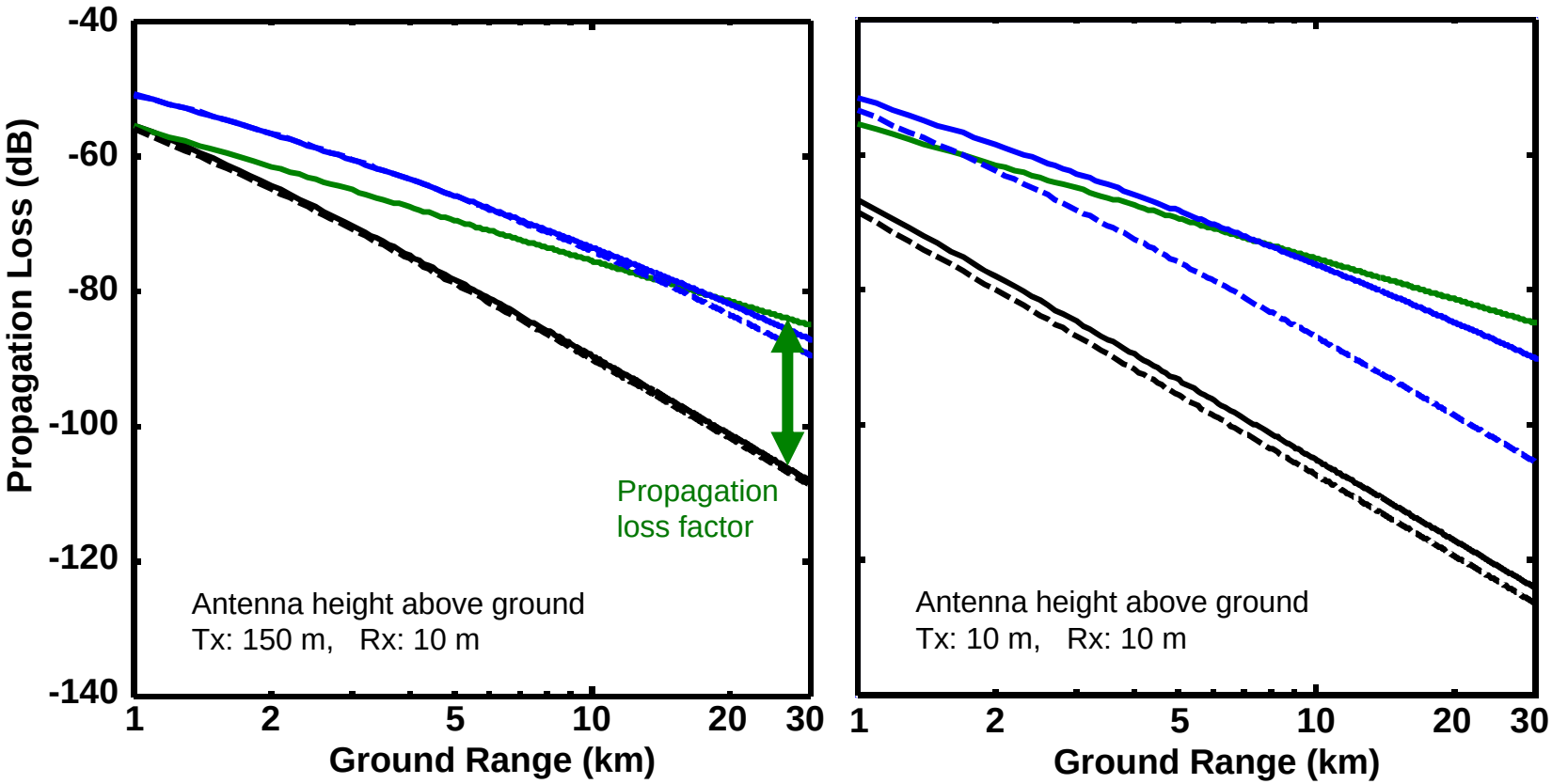
Space Plus Surface Wave Propagation Loss

Propagation loss estimated with Norton's approximation over flat ground surface



Propagation at 14.3 MHz
In free space
Over sea water
Over lossy ground (ε_r = 30, σ = 0.01 S/m)

Legend:
Space wave + surface wave
Space wave only

MIT LL Implementation of GRWAVE solution allows separability of the space and ground wave terms

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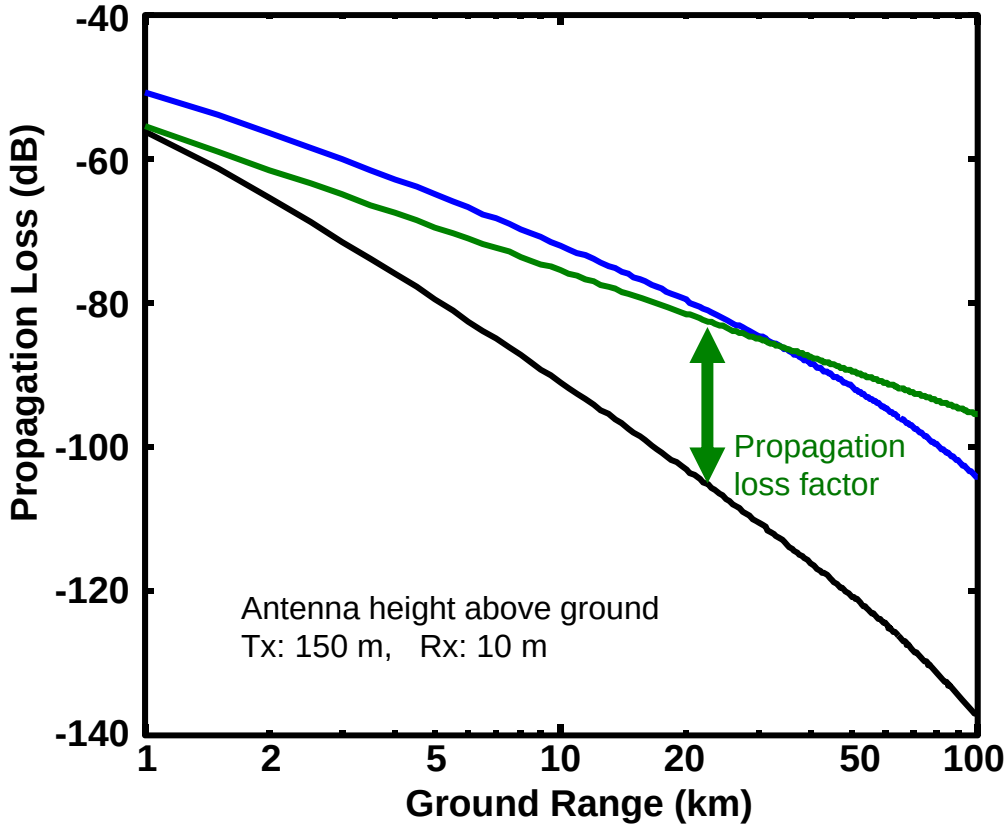
Ground Wave Propagation Loss Using GRWAVE

Propagation loss estimated with GRWAVE over spherical earth surface



Propagation at 14.3 MHz

In free space
- Isotropic Tx and Rx antenna

Over sea water
- Small dipolar Tx

Over lossy ground
- (ε_r = 30, σ = 0.01 S/m)
- Small dipolar Tx

NEC will be used to compute scattered level at a given range and GRWAVE is used to shift solutions in range

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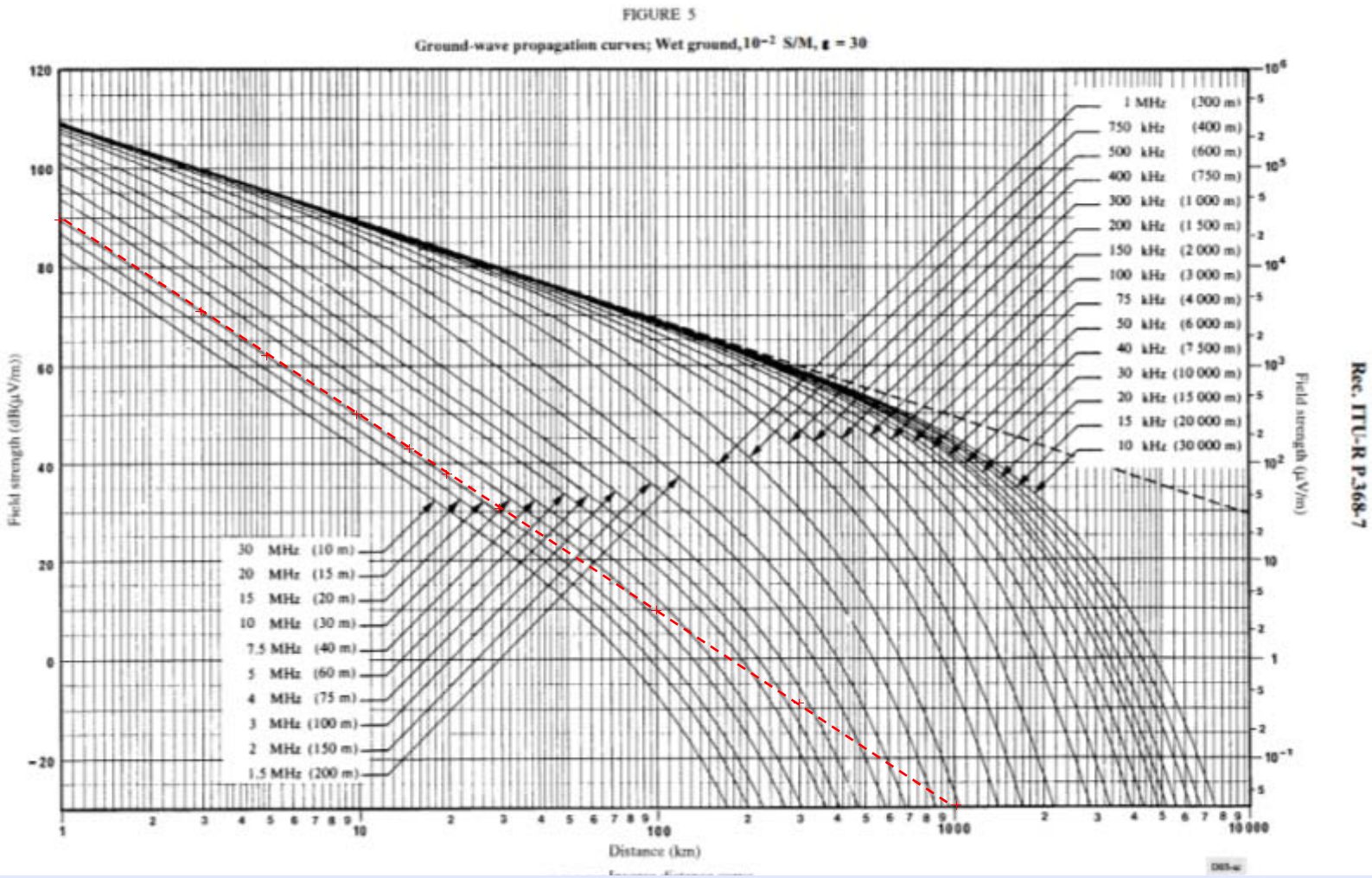
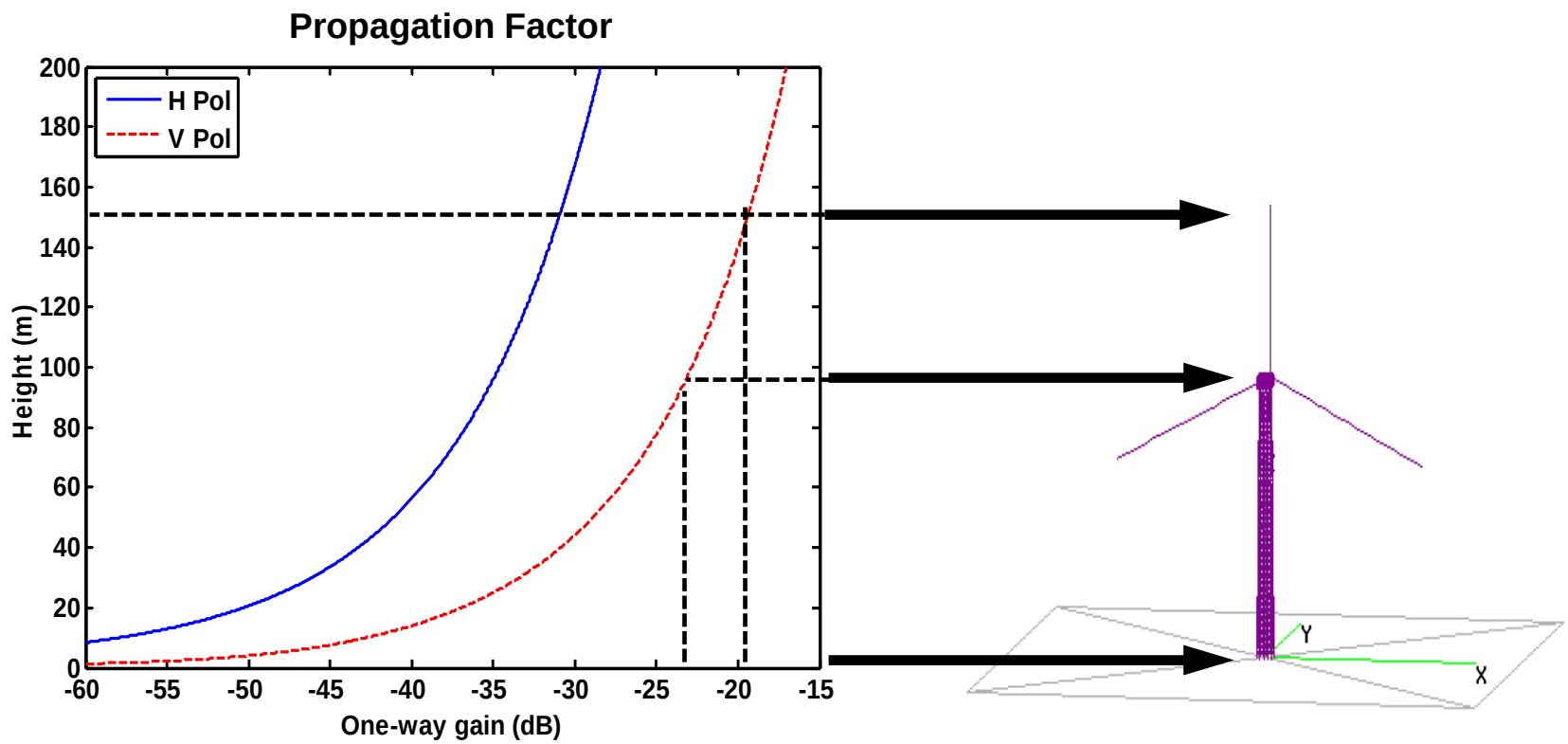
NEC Computation of Ground-Wave vs Range



NEC matches ground wave calculations (GRWAVE) out to about 25 km (using monopoles with 1λ radials)

Multipath Propagation Calculation vs Height with Turbine at 10 km Range



Tower: 96.76m Height
Blades: 50 m Length
Ground: $\varepsilon_r = 13$, $\sigma = 0.005$ S/m
Antenna ht: 3 meters

Propagation Factor ranges from -19 dB at the top of the blade to less than -27 dB at bottom of blade – weighs the higher portions of the turbine more heavily than the lower portions

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Propagation Tools Thoroughly Tested and Understood

- **Tools producing consistent results for this application**
  - **GRWAVE, NEC, MIT-LL GRWAVE, MIT-LL MPATH**
  - **Ground wave and space wave contributions understood**
  - **NEC valid in Sommerfeld region**
    - **Benefit to using NEC is that multiple effects can be computed simultaneously**

- **Future propagation modeling likely to be performed using VTRPE**
  - **Parabolic Equation (PE) propagation software is a full field approximation for site-specific scenarios**
  - **Have VTRPE examples later in this brief**

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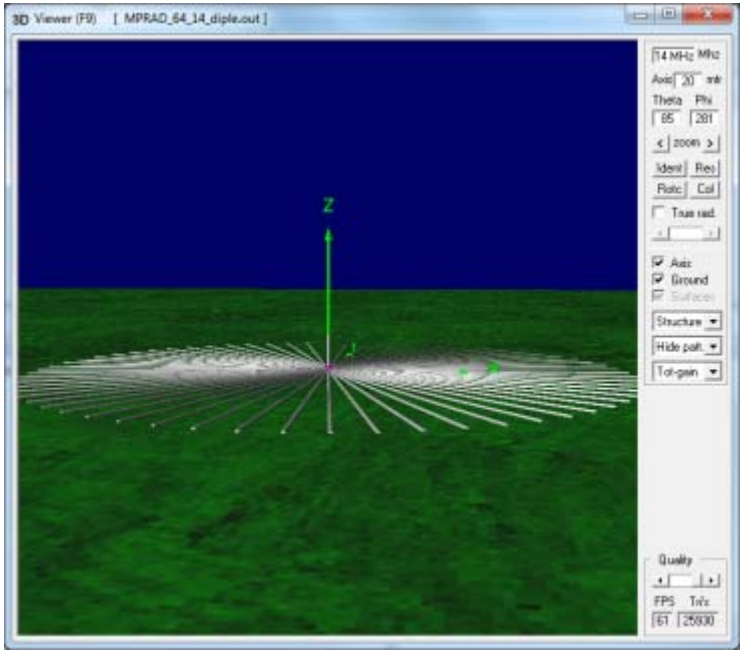
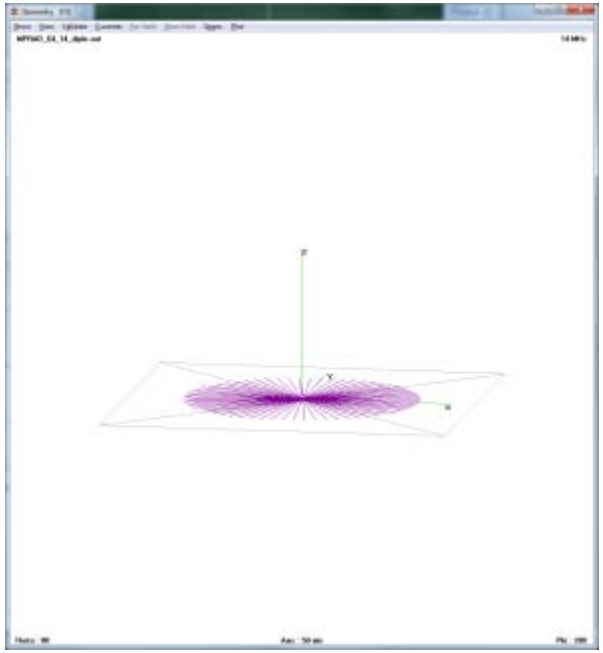
What Receive Antenna to Use?

- **ROTHR Uses a TWERP antenna that provides front-to-back isolation**
  - **Uses 100’ ground screen**
- **This quick-look study only computing front-lobe main-beam response**
  - **Monopole antenna used with up to 64 120-foot radials**





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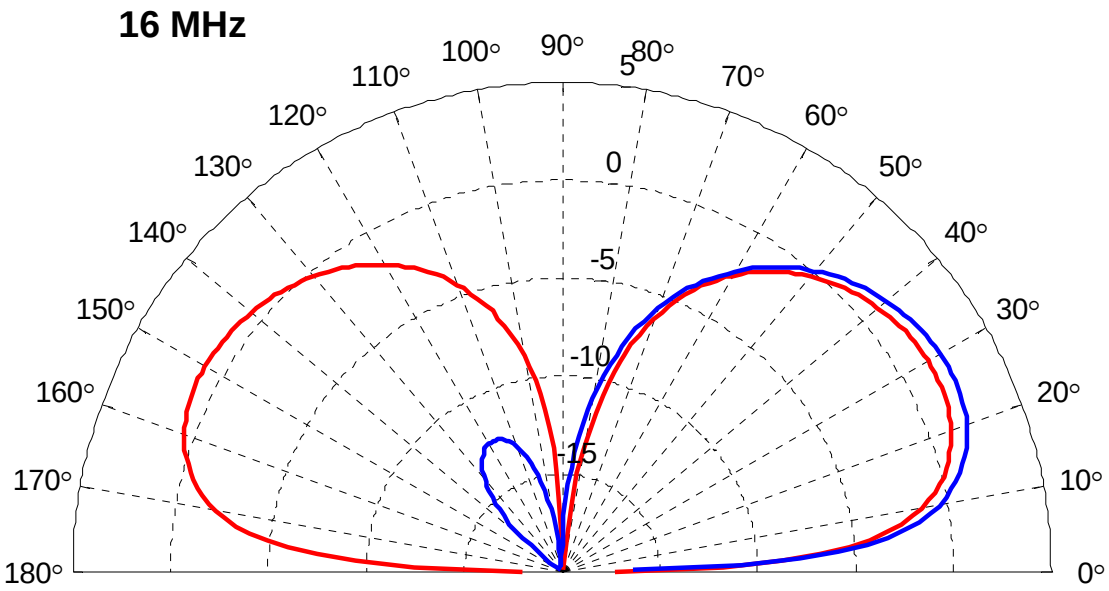
TWERP and Monopole Elevation Gain Patterns Comparison

Monopole Height = 15.5 ft
TWERP Separation = 13.8 ft
Medium Ground (σ=0.005 S/m, ε=13)



Result Provided by Henry Thomas, MIT LL

Directivity close at the 5-degree elevation direction of the main clutter signal

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  - Propagation modeling
  - Antenna
  - Turbine modeling
    - Model development and monostatic testing
    - Bistatic RCS
    - Model results
  - Radar system effects
  - Future modeling work
- Summary
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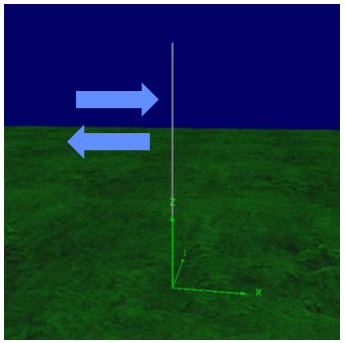
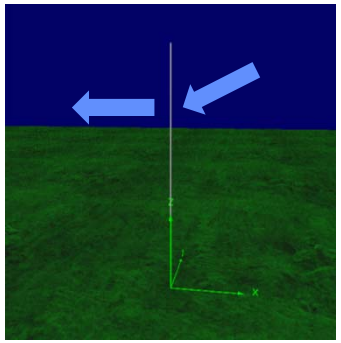
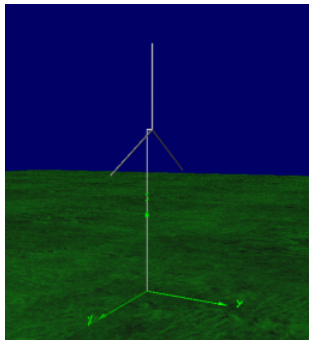
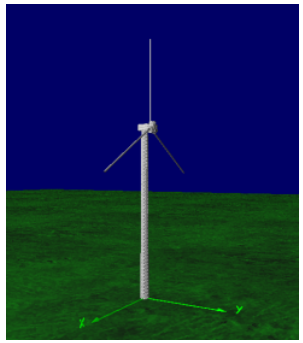
Model Development Progression

Long Wire Monostatic RCS → Long Wire Bistatic RCS → 5-Wire Turbine Model → Full Mesh Turbine Model →









- **Ground types**
  - **Free space (no ground)**
  - **Perfect Electric Conductor (PEC) Ground**
  - **Real ground (e.g., average ground with ε_r= 13, σ = 0.005 S/m)**

NEC Monostatic RCS Calculations for Long Wire

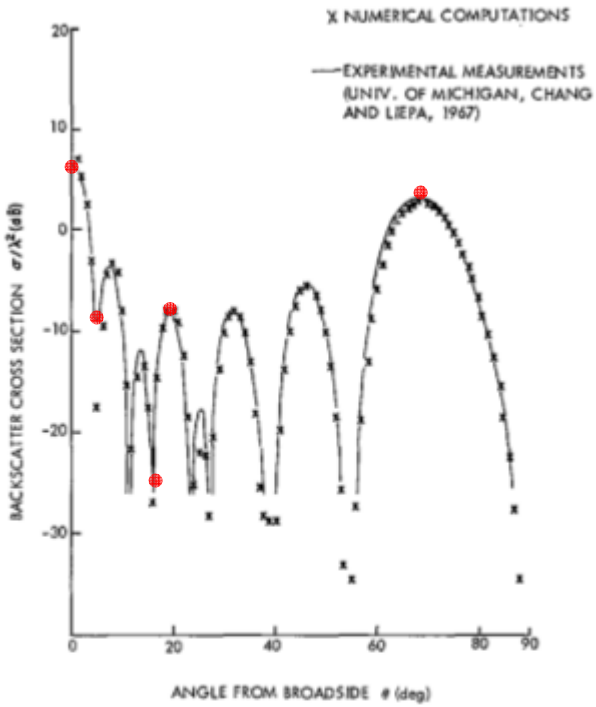
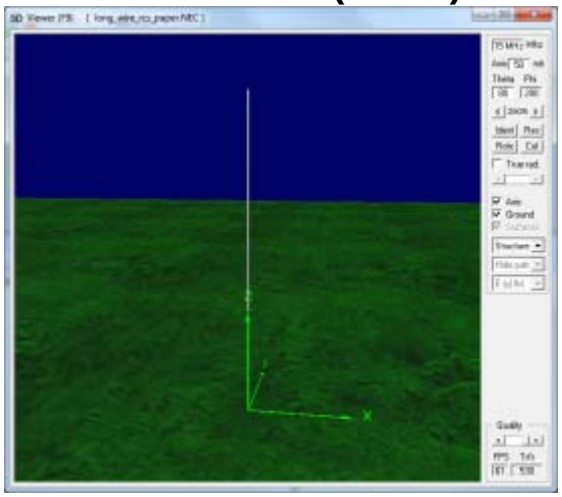


Fig. 1. Numerical–experimental comparison for a 5.221λ straight wire (wire radius $a/\lambda = 6.27 \times 10^{-3}$).

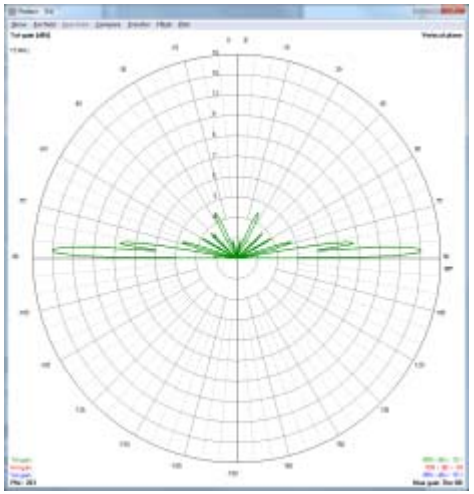
- NEC Spot Check

- **NEC Broadside Calculations**
  - **Free space: 7.46 dB**
    (Add 26 dB for λ=20 m: 33.46 dBsm)
  - **PEC Ground: 19.5 dB (45.5 dBsm)**
  - **Average ground (2.5 degrees from broadside): 15 dB (41 dBsm)**

5.221 λ Wire (104 m)

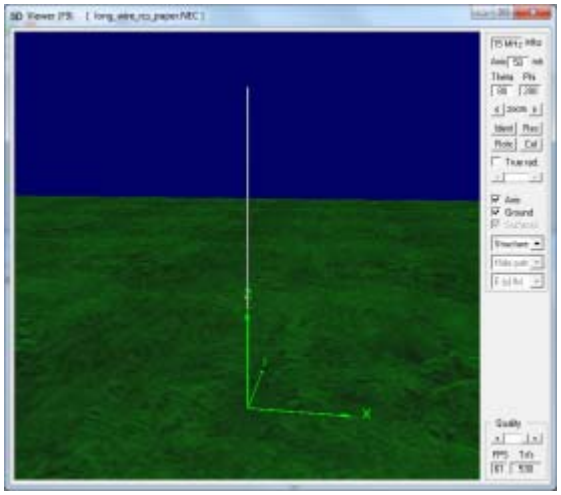


Avg. Ground 13/.005



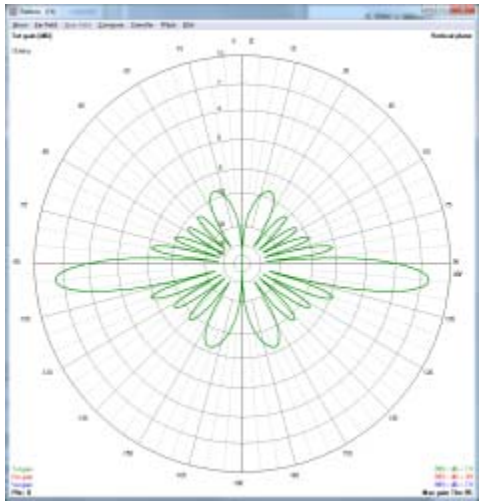
NEC Bistatic RCS Calculations for Long Wire

5.221 λ Wire (104 m)

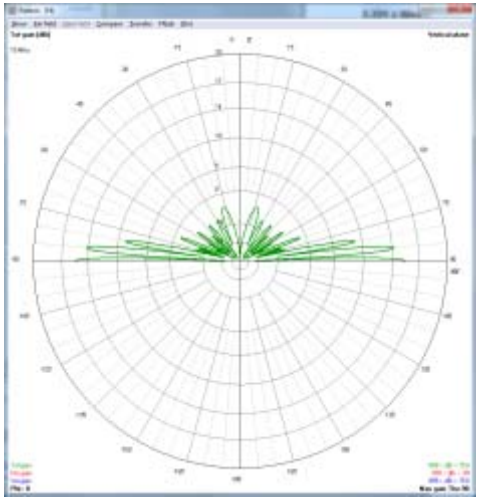


- **NEC Bistatic RCS Calculations**
  85º incidence
- **RCS at 0º scattered angle (Add 26 dB to plot values (λ=20m))**
  - **Free Space: 4 + 26 = 30 dBsm**
  - **PEC: 15.5 + 26 = 41.5 dBsm**
  - **Real Ground: = 0 m^2 (-125 dB) null at 0º**
    -2 + 26 = 24 dBsm up 1º
    29 dBsm up 2º

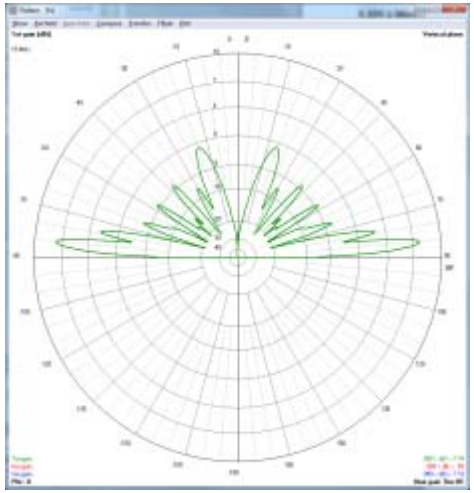
Free Space



PEC



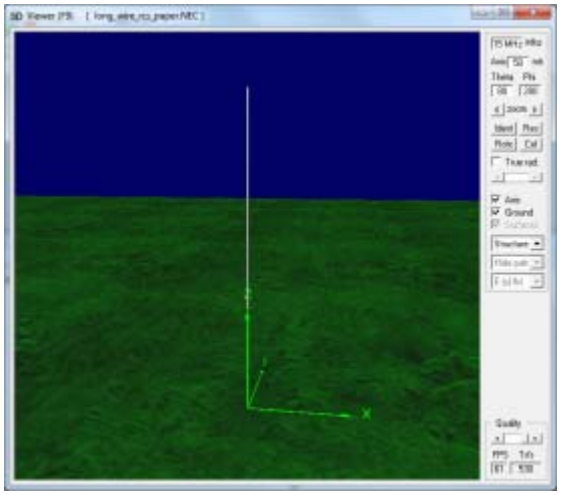
Avg. Ground 13/.005



Scattered Power Ratio Calculations for Long Wire

"Back of the Envelope"

5.221 λ Wire (104 m)



- RCS is defined at a ratio of incident and scattered power density:

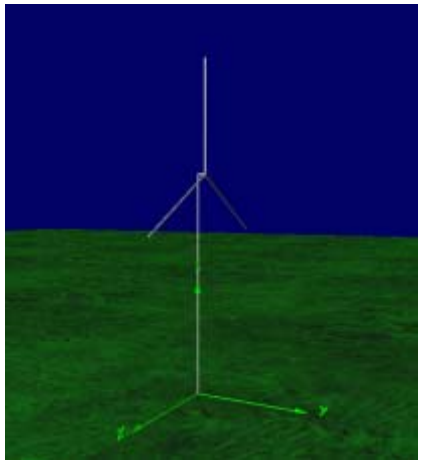
$$\frac{S_s}{S_i} = \frac{\sigma}{4\pi R^2}$$

- At 25 km, $4\pi R^2$ = 99 dB and power ratios for the long wire are
  - Monostatic free space: 33.5 dBsm – 99 = -65.5 dB
  - Monostatic PEC Ground: 45.5 dBsm – 99 = -53.4 dB
  - Monstatic average ground (2.5 degrees from broadside): 41 dBsm – 99 = -58
  - Bistatic free space: 30 dBsm – 99 = -69
  - Bistatic PEC = 41.5 dBsm – 99 = -57.5
  - Bistatic average ground = 24 dBsm (up 1º) -99 = -75

Simple 5-Wire Model – Monostatic RCS

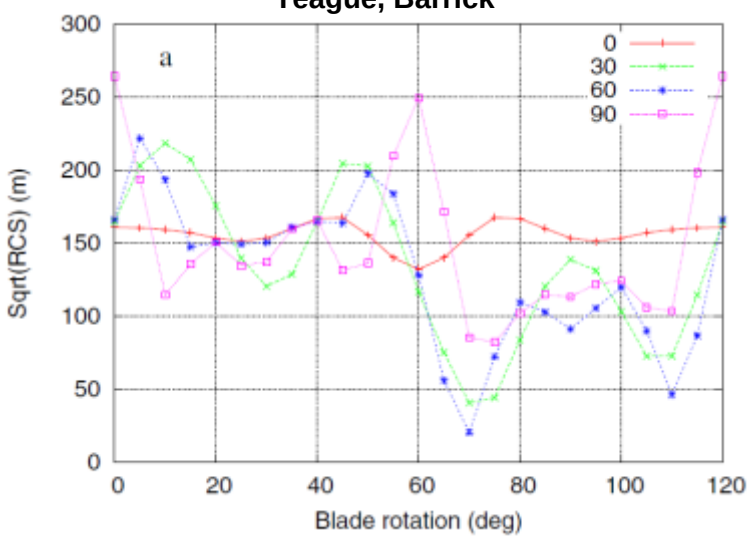
Validation of 5-wire NEC turbine model

65-meter tower, 42-meter blades, PEC Ground

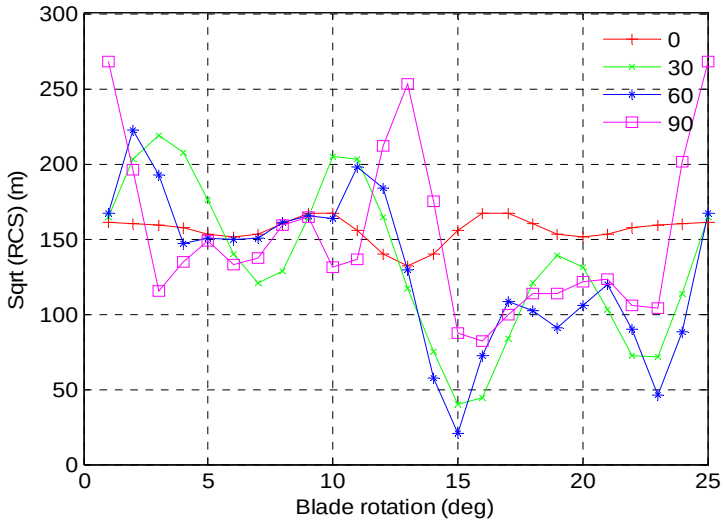


IEEE OCEANS 2012 Conference reference

Teague, Barrick



MIT LL NEC 4.2



Near exact agreement between Barrick NEC 2 model and Lincoln NEC 4.2 Model

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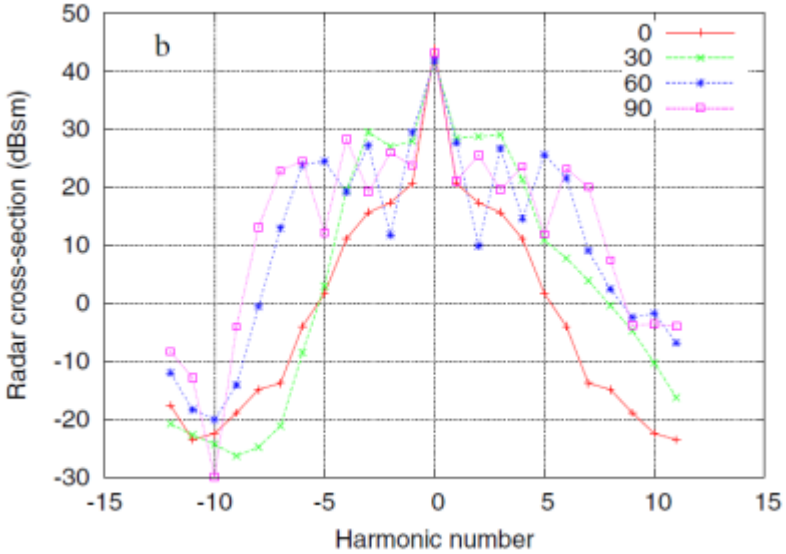
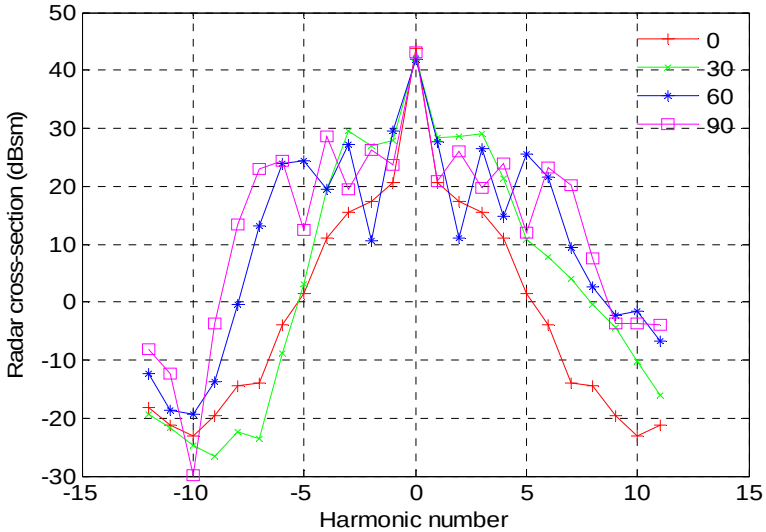
Simple 5-Wire Model – Doppler Spectra

5-wire tower

Teague, Barrick



Lincoln



Both RCS and Doppler spectra agreement with Barrick for monostatic PEC case

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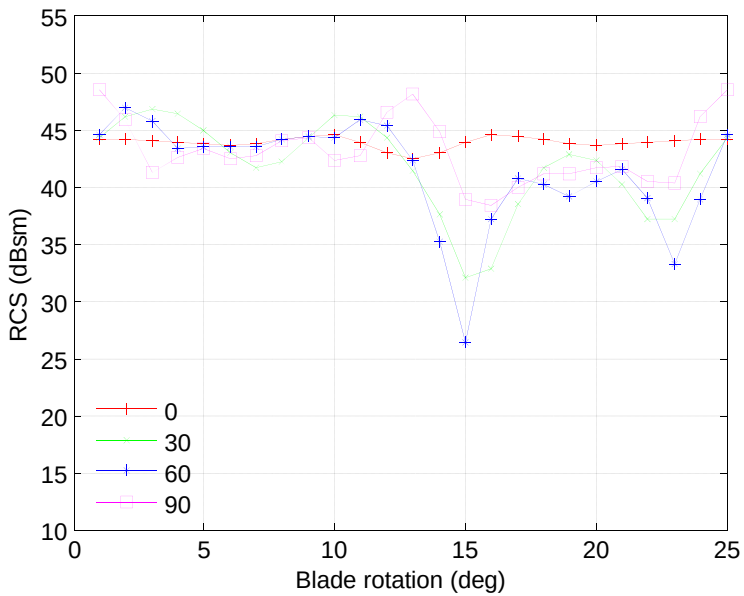
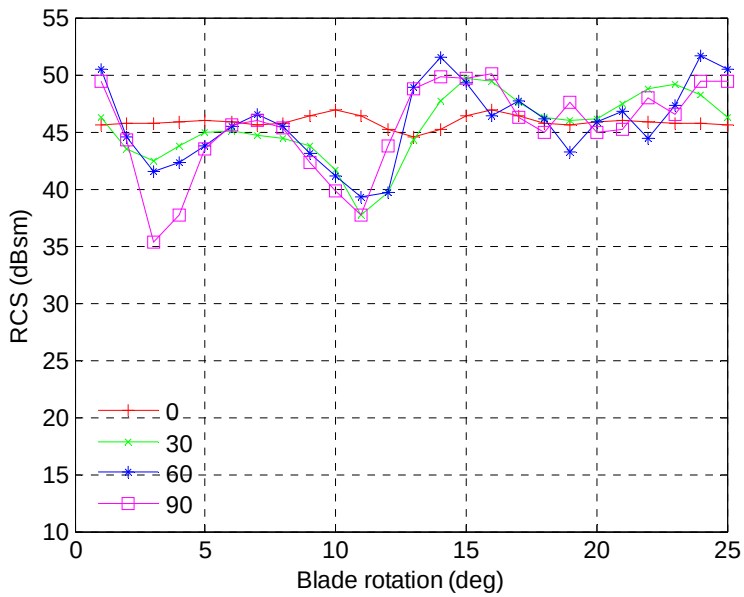
Evolve Wire Model for Current Study

65-meter tower height → **100-meter tower height**

42-meter blade length → **50-meter blade length**





RCS increases by several dB for larger turbine for this PEC example

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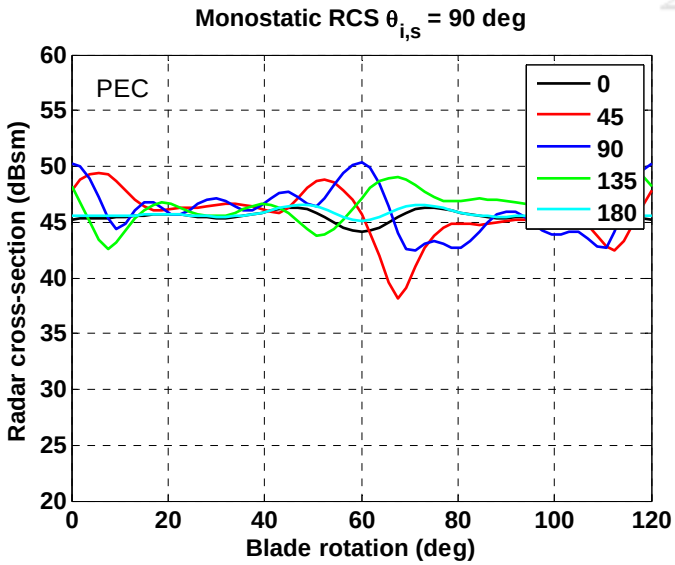
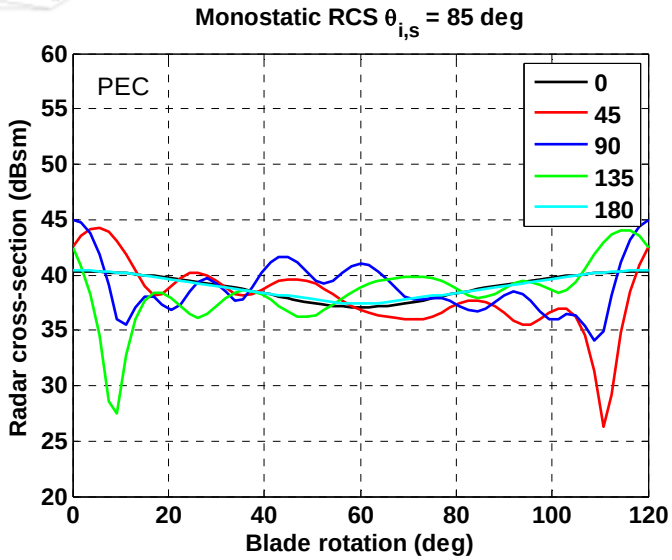
Monostatic RCS at 85 and 90-Degree Incidence Angles

90º Incidence



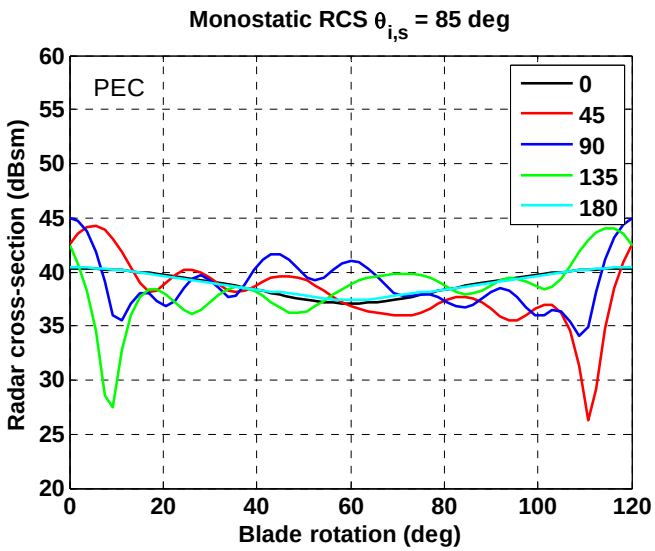
85º Incidence



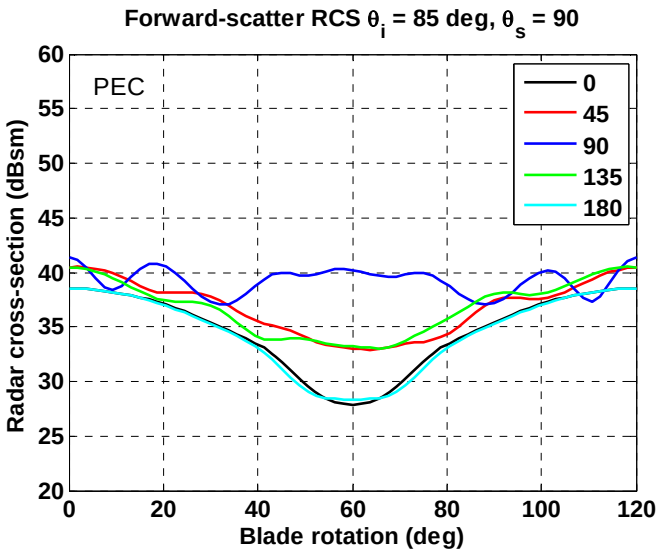
RCS strongly depended on incidence angle for PEC case (dropped by almost 10 dB)

Monostatic and Bistatic RCS

85º Incidence Monstatic



85º Incidence, 90º Scattered Angle



Oblique incidence combined with forward-scattering produces even greater RCS reduction for PEC Case

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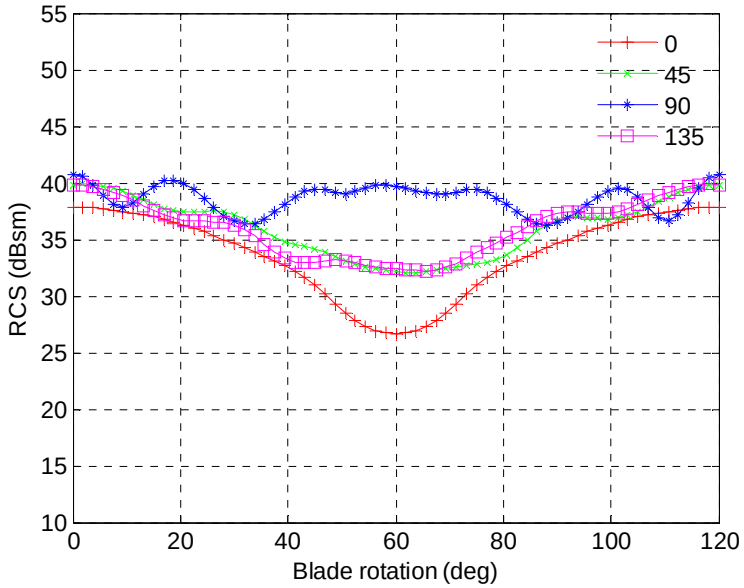
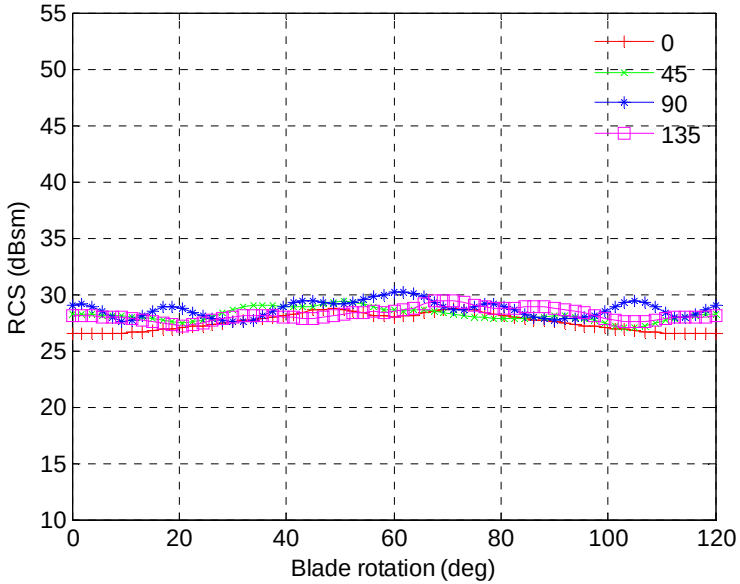
Bistatic RCS with Real Ground

θ_i=85 deg, θ_s=89.5

PEC



Real ground ε_r=30, s=.01



Real ground further reduces effective RCS and flattens out spatial variation – may be due to multipath propagation weighting the higher portions of the turbine more heavily and attenuating the blade-column interaction.

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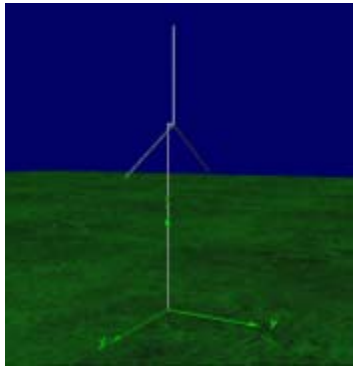
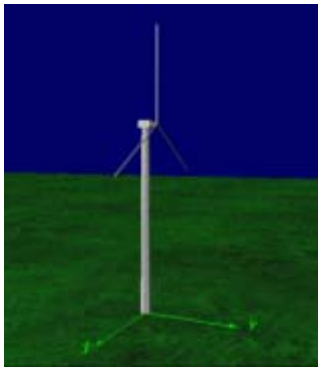
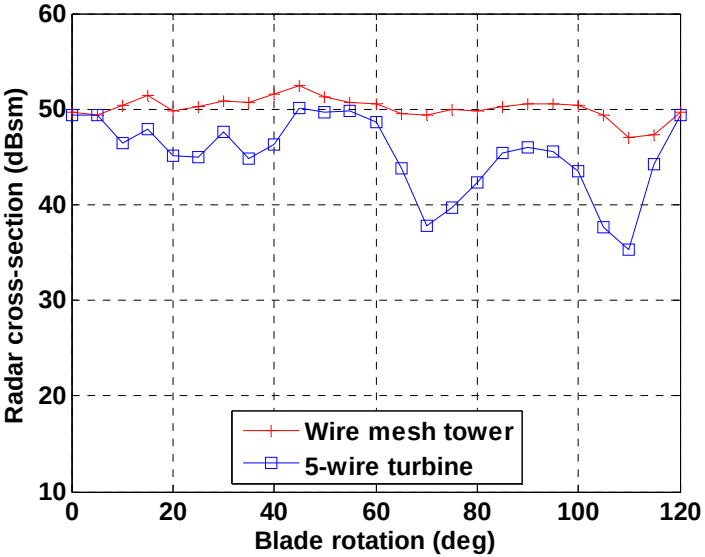
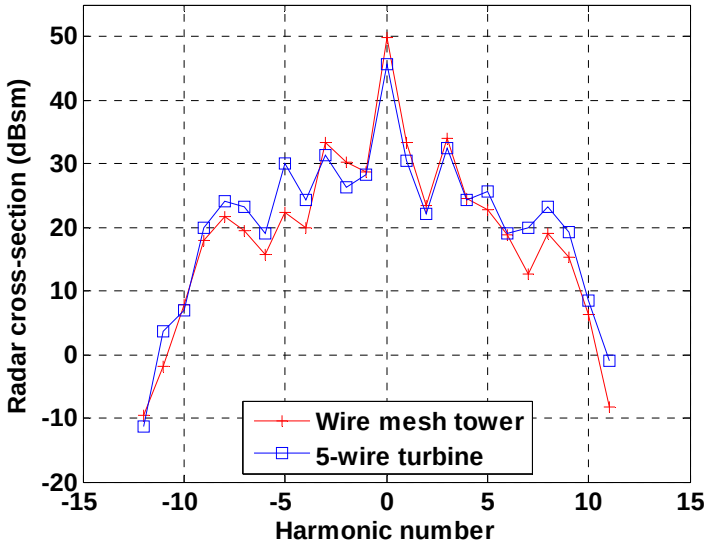
Monostatic RCS and Spectra for 5-Wire and Full Mesh Model









Simple 5-wire model captures much of the spectral behavior for monostatic PEC case

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Outline

- Introduction
  - Bottom line up front
- Modeling approach
  - Propagation modeling
  - Antenna
  - Turbine modeling
    - Model development and monostatic testing
    - Bistatic RCS
    - Model results
      - Principal results for one turbine, one element
  - Radar system effects
  - Future modeling work
- Summary
- Backup and additional information

RCS Modeling/Simulation Block Diagram

MATLAB-based NEC driver and post processor

Input parameters

Tower
- Upper diameter
- Lower diameter
- Height
- Number of faces

Turbine
- Nacelle angle
- Blade wire length
- Blade wire diameter
- Number of rotor positions
- Rotation direction

Radar System and Environment
- Frequency
- Incident, scattering geometry angles
- Incident wave polarization
- Underlying surface electrical parameters

Desired Output
- Radar cross section
- Electric field

MATLAB Pre-processor/initiator .m

Read tower, nacelle, hub, blade descriptors

⇩

Calculate wire mesh positions, orientations and sizes

⇩

Read radar system / environment / output parameters

⇩

NEC input file generation

⇩

System Call to NEC executable program

NEC executable program

Parallelize turbine blade angle computations by dividing among 64 processors

1

Lawrence Livermore National Laboratory Numerical Electromagnetics Code NEC-4.2

64

MATLAB Post-processor .m

Specify NEC output parameter of interest (RCS, electric field, current)

⇩

Parse NEC .out file

Thinkmate 64-processor AMD Opteron series 6200 Computer

Two Modes of Operation

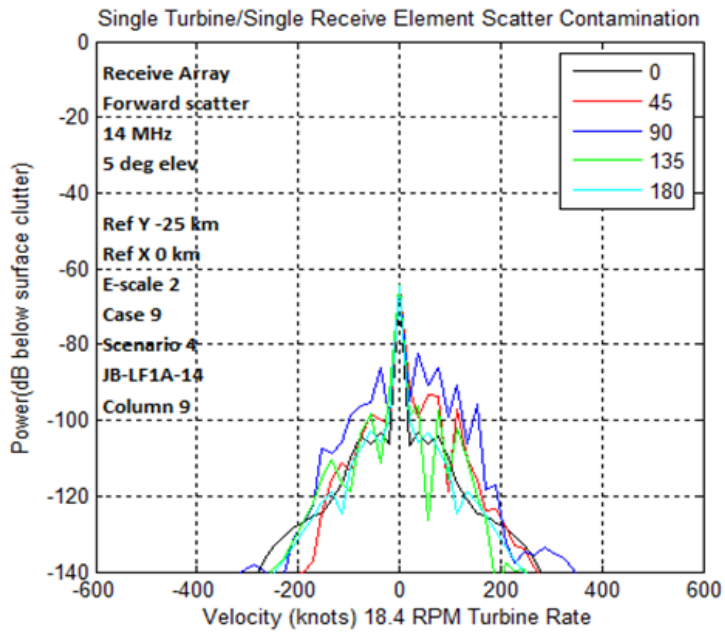
- **"All in One" or "One-Step" approach where direct path and scattered paths are measured in a single NEC run**
  - **Required modifications to NEC 4.2 source code which was obtained from Lawrence Livermore National Laboratory**
    - **Precision of NEC output files was increased**

- **"Two-Step" approach where the scattered field is measured separately from the direct path with "surface wave mode" feature of NEC turned on**
  - **Measured field at antenna location converted to received voltage using the antenna-effective height**
  - **Direct and scattered path ratio formed and Doppler spectra computed**

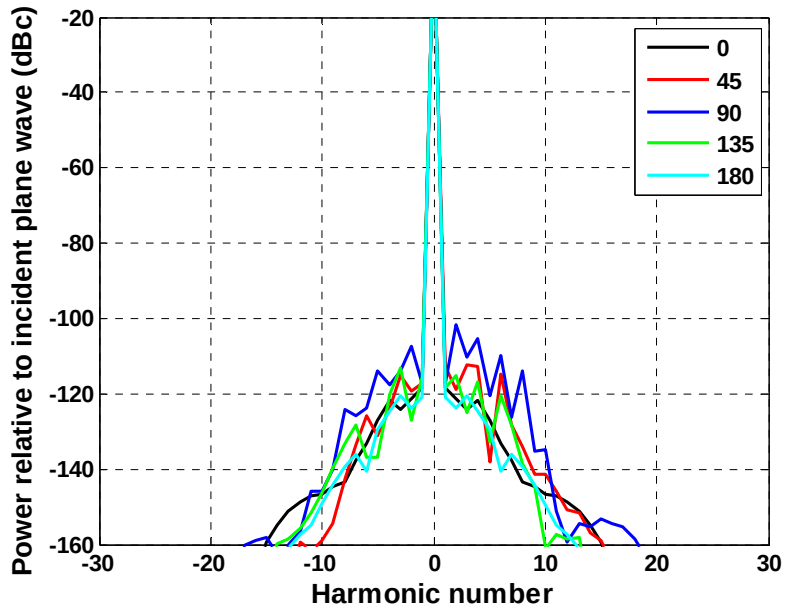
One-Step and Two-Step Examples

Single Turbine, Single Receiver Element

ROTHR Study Figure 5



Lincoln Calculation Using ROTHR Model



Two-step result shows turbine scatter only

One-step result shows Direct and Scattered signal in a single run

14 MHz, 25 km Range
5 degree grazing, forward scatter

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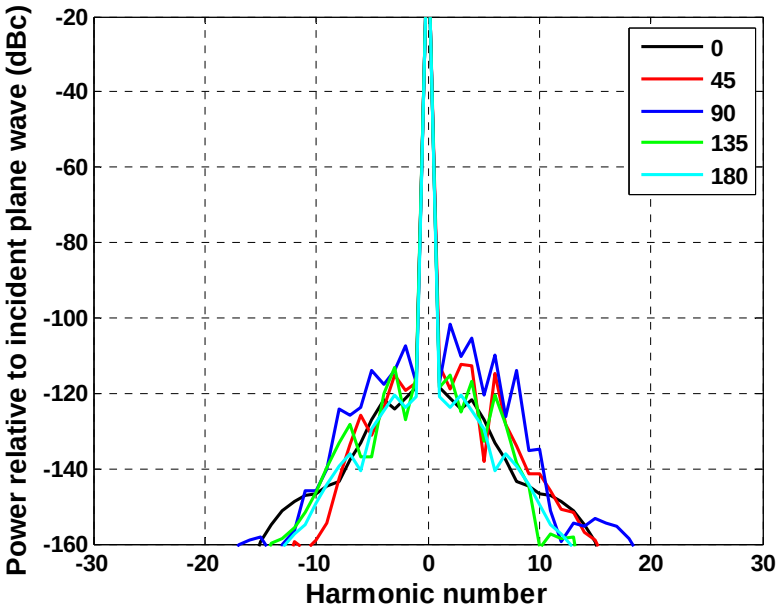
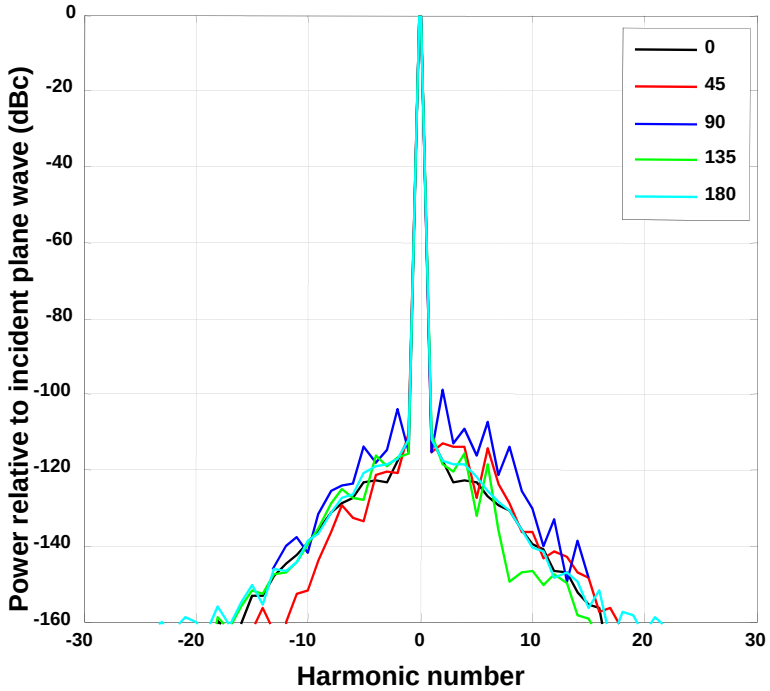
Turbine Model Comparison

Lincoln One-Step Calculation Using ROTHR Model



Lincoln Dense Mesh Model

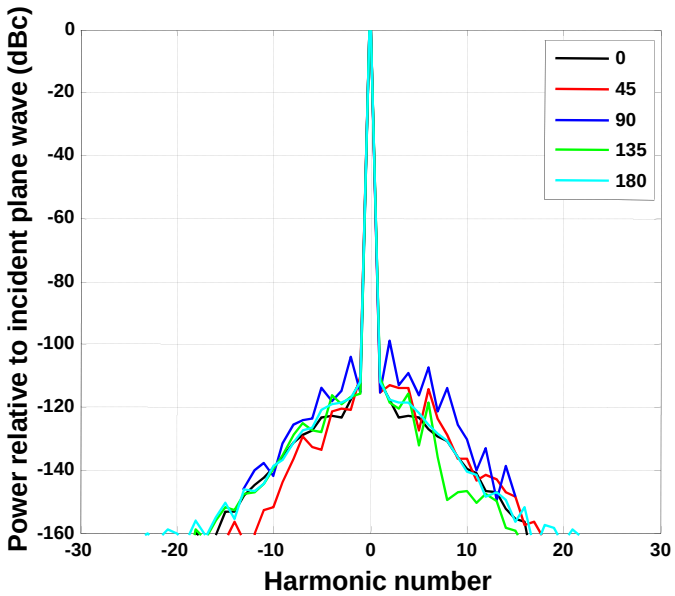


14 MHz, 25 km Range
5 degree grazing, forward scatter

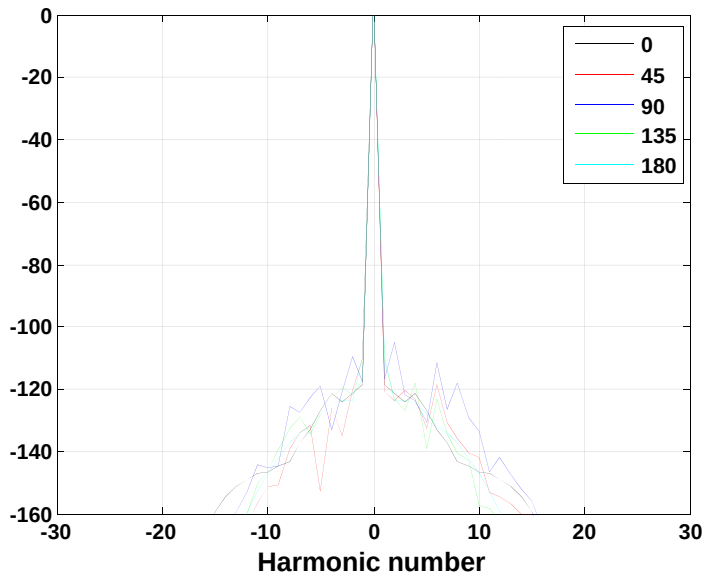
ROTHR and Lincoln turbine models predict very similar scattering spectra

Turbine Model Comparison (cont.)

Lincoln Dense Mesh Model



Lincoln 5-Wire Model

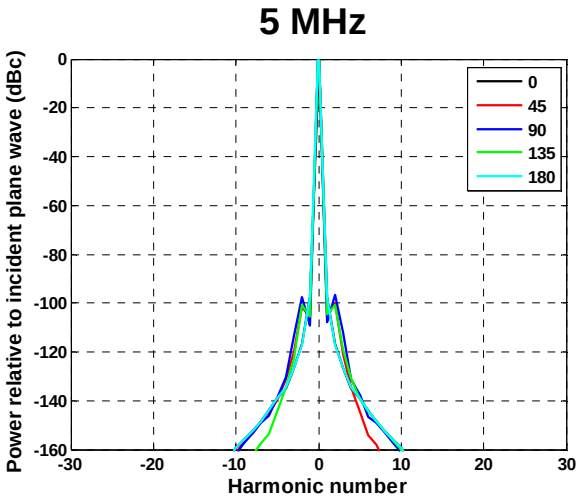


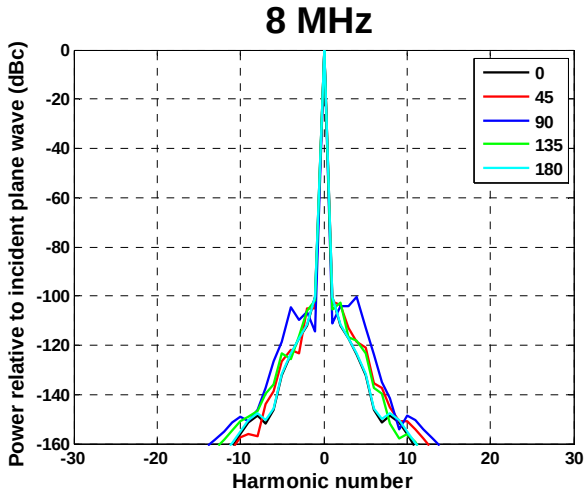
14 MHz, 25 km Range
5 degree grazing, forward scatter

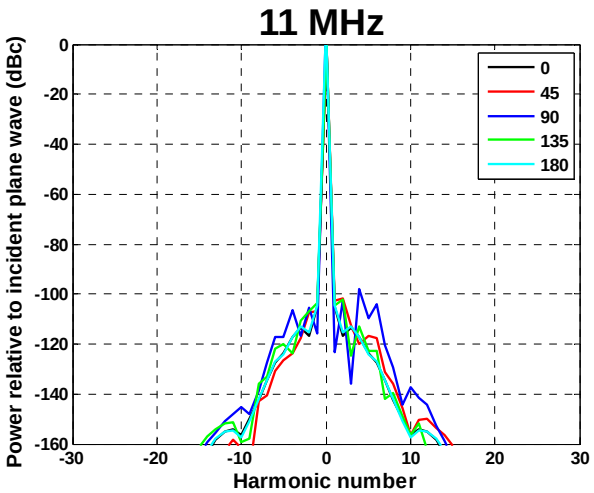
Simple 5-wire model captures much of the spectral behavior but scattering is slightly weaker

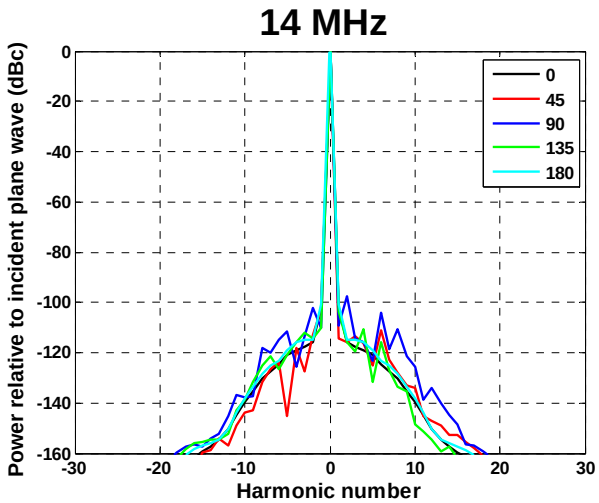
Frequency Dependence of Turbine Spectra

5-wire model, 97m height, 100m blade diameter









- 15 km separation
- Average ground (13, .005)

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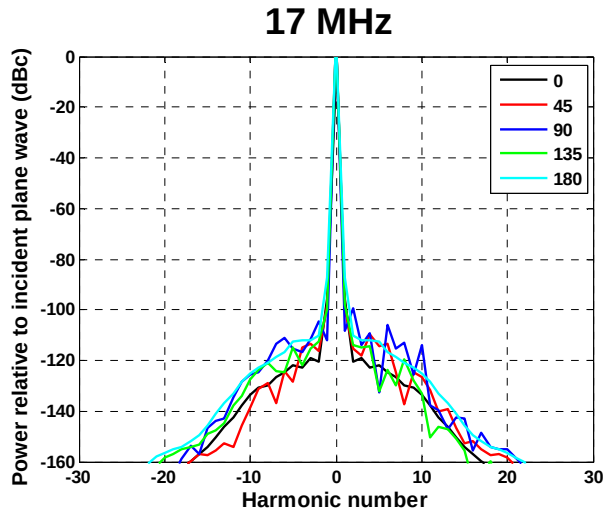
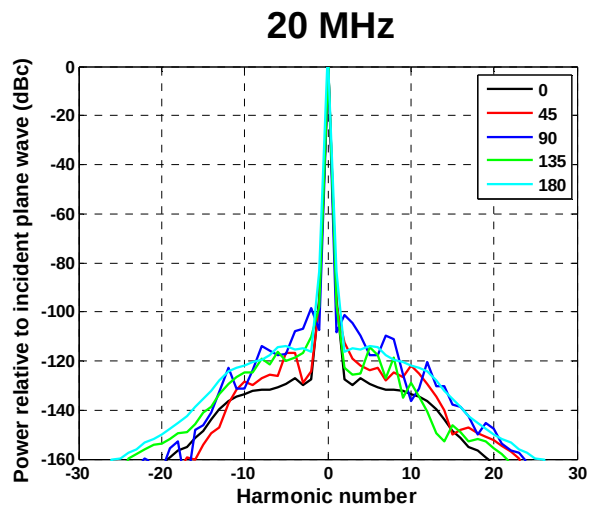
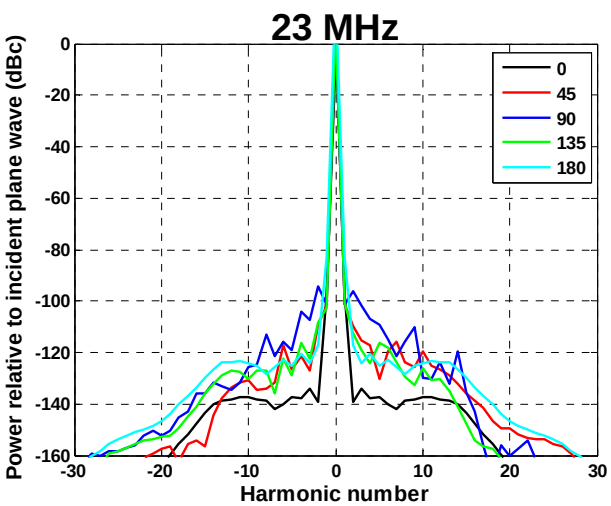
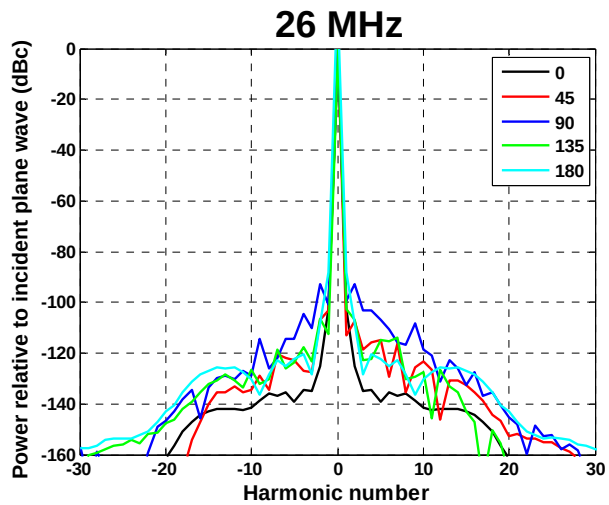
Frequency Dependence of Turbine Spectra

5-wire model, 97m height, 100m blade diameter









- 15 km separation
- Average ground (13, .005)

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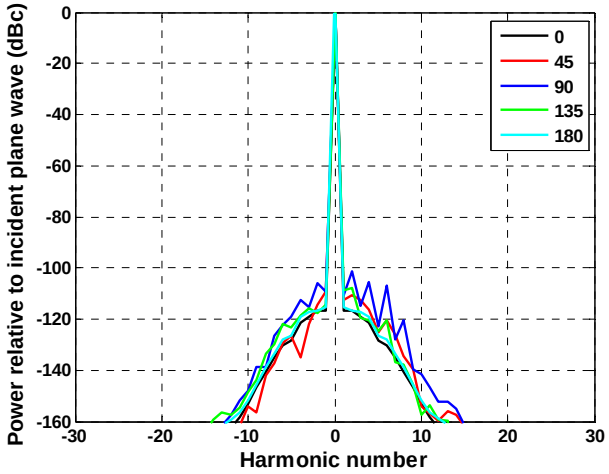
5-Wire Model Spectra for Three GE Turbines

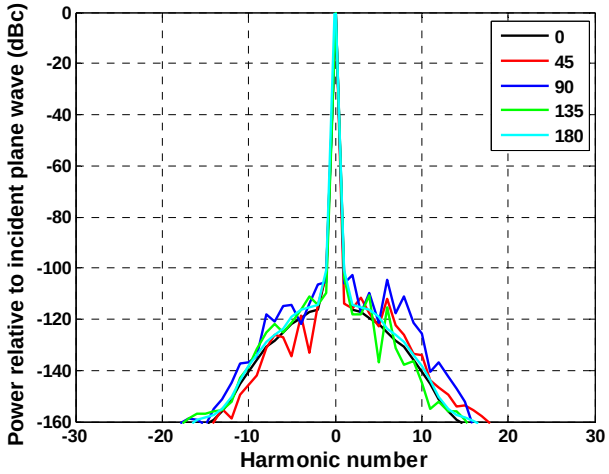
Turbine Model	Hub Height	Blade Diameter
GE 1.85-87	85 m	87 m
GE 2.85-103	97 m	103 m
GE 2.5-120	139 m	120 m

F=14 MHz

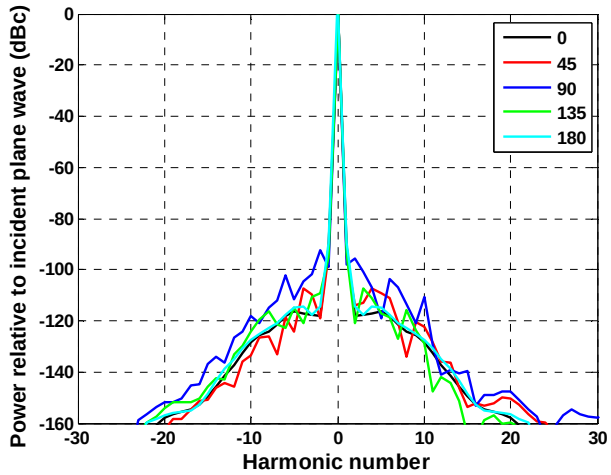
GE 1.85-87



GE 2.85-103



GE 2.5-120



5-Wire model, 15 km receiver-turbine distance, average ground (ε=13, σ=0.005)

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  - Future modeling work
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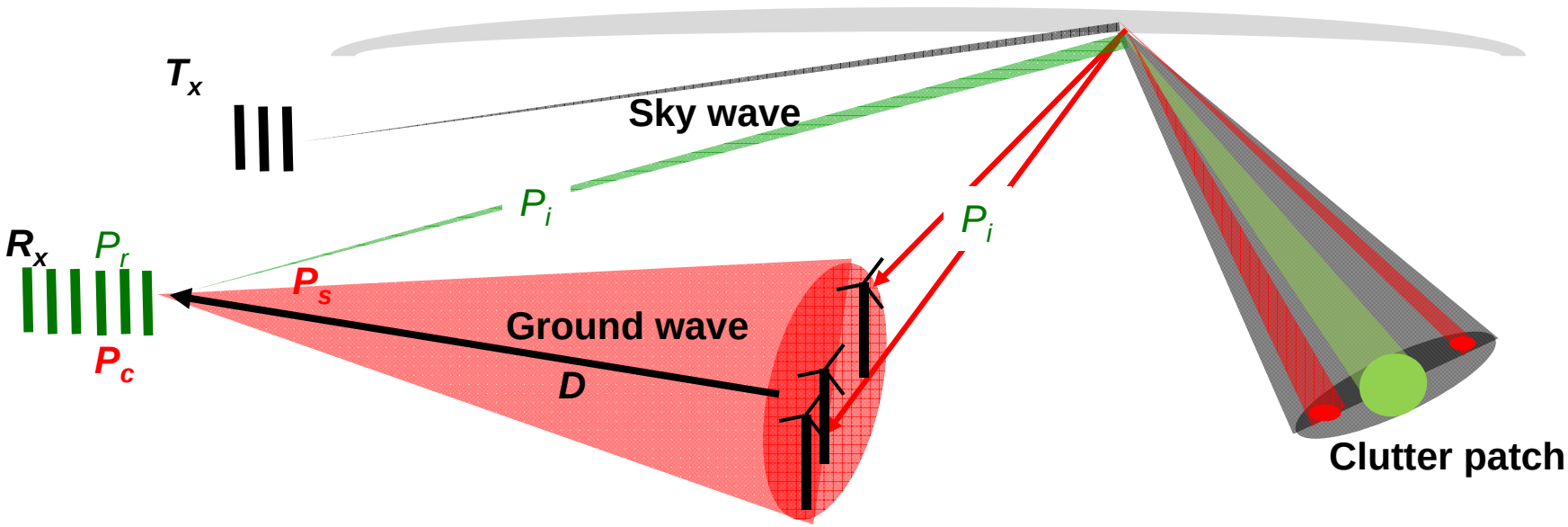
Wind-Farm Clutter Interference



$$\left[\frac{P_c}{P_r}\right]_M = \left[\frac{P_c}{P_r}\right]_1 \left[\frac{T_x}{R_x}\,\mathit{Beam\ shape}\right] \left[\begin{array}{c}\mathit{Near\ field\ array\ focusing}\\ \mathit{loss\ of\ M\ turbines}\end{array}\right]$$

Turbine-to-incident clutter level

Single turbines

Effective number of turbines

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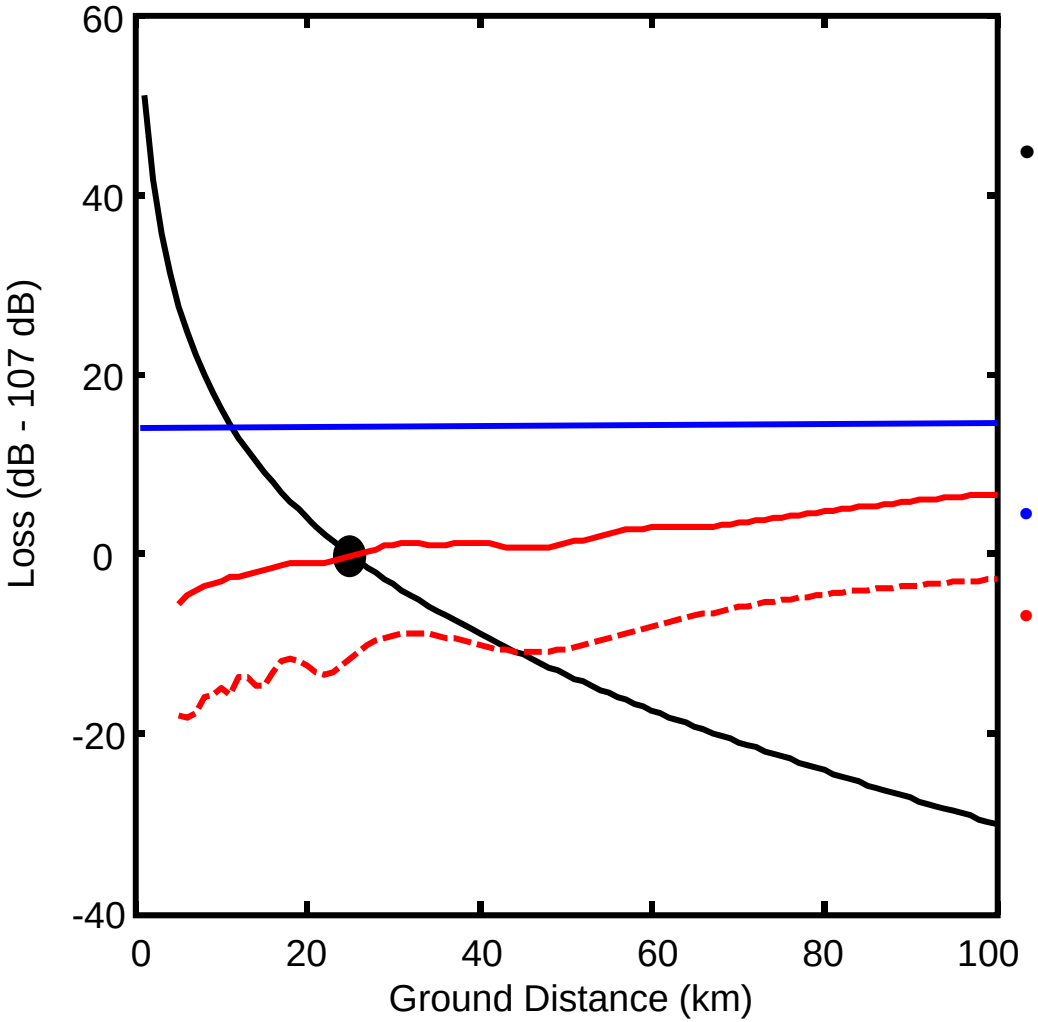
Adjustment Factor for Wind-Farm Interference



- GRWAVE propagation loss over wet ground
  - ε_r = 30
  - σ = 0.01 s/m
  - Receiving antenna: 10 m
  - Transmitting antenna: 150 m
- Ratio of Tx/Rx beam width
- Near field array factor
  - Single turbine
  - Wind farm (5 x 5, 1-km spacing)

Used to scale single-turbine, single-element result to entire wind-farm

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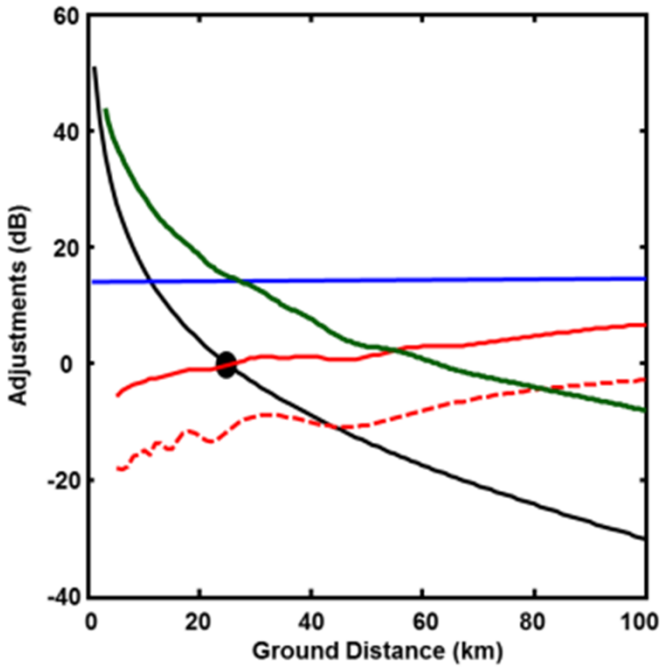
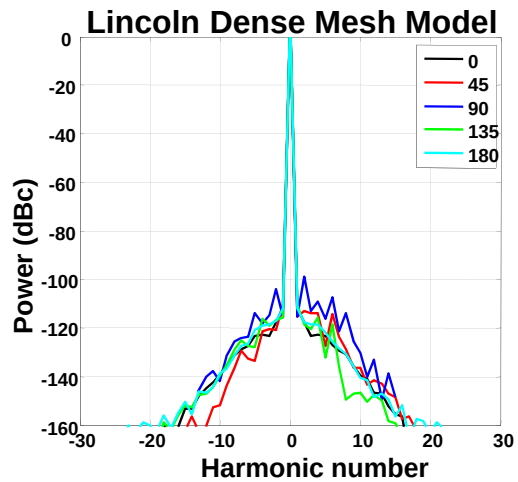
Standoff Distance Determination

Adjustment Factor (5x5 Farm)



+

Single-Element Single-Turbine Spectra



Standoff

Adjust single-element single-turbine spectra to achieve standoff distance estimates

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Error Analysis

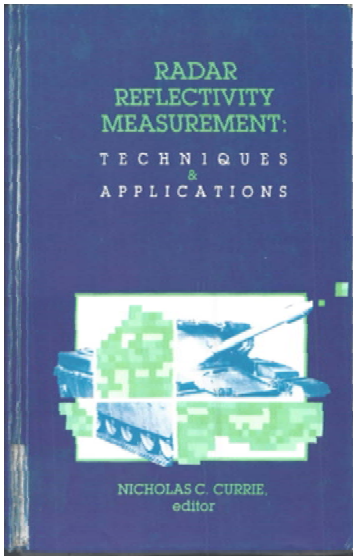

Table 4.2
Summary of Typical Errors

	μ Microwave		Millimeter-Wave	
	Land (dB)	*Sea* (dB)	*Land* (dB)	*Sea* (dB)
REFERENCE REFLECTOR CALIBRATION				
Radar Positioning	−0.5	−0.5	−0.5	−0.5
Corner Reflector Positioning	−0.3	−0.3	−0.3	−0.3
Corner Reflector Accuracy	−0.2	−0.2	−0.2	−0.2
Multipath	±1	±1.5	±0.5	±1
Drift, Sampling, Recording	±1	±1	±1	±1
Calibration Curve Matching	±1	±1	±1	±1
Accumulated Error	−1 ± 3	−1 ± 3.5	−1 ± 2.5	−1 ± 3
SIGNAL GENERATOR CALIBRATION				
Path Loss Uncertainty	±0.5	±1	±1	±1.5
Spectrum Equivalence	±0.5	±0.5	±0.5	±0.5
Drift, Sampling, Recording	±1	±1	±1	+1
Calibration Curve Matching	±1	±1	±1	±1
Accumulated Error	±3	±3.5	±3.5	±4

- **Standard practice for reporting expected RCS measurement accuracy is to tabulate all error sources**
  - **Worst case condition is to assume all errors combine at their maximum value**
    - **Can be shown as error bars on plots**
  - **Root-Sum-Squaring (RMS) the errors results in a reduced expected error**
    - **Unlikely that all errors will combine in the same direction**
- **Modeling error sources for this problem are 1) Propagation, 2) Turbine Modeling, and 3) Antenna modeling**

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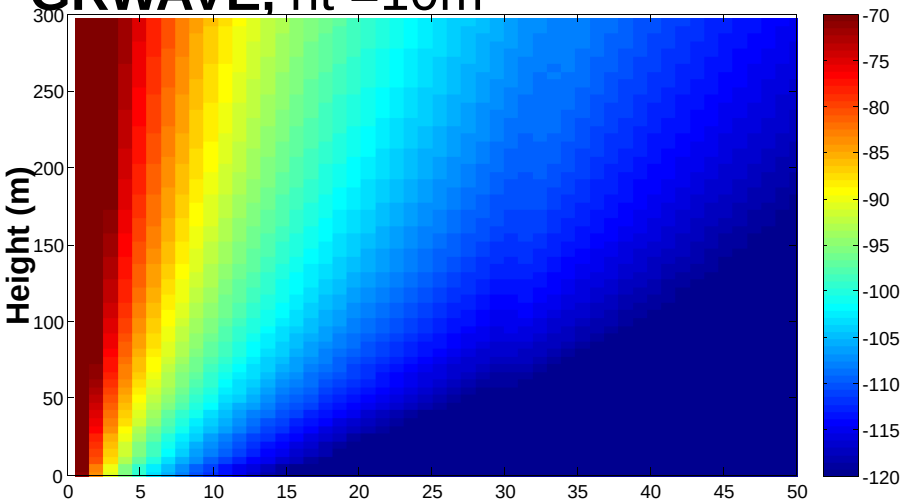
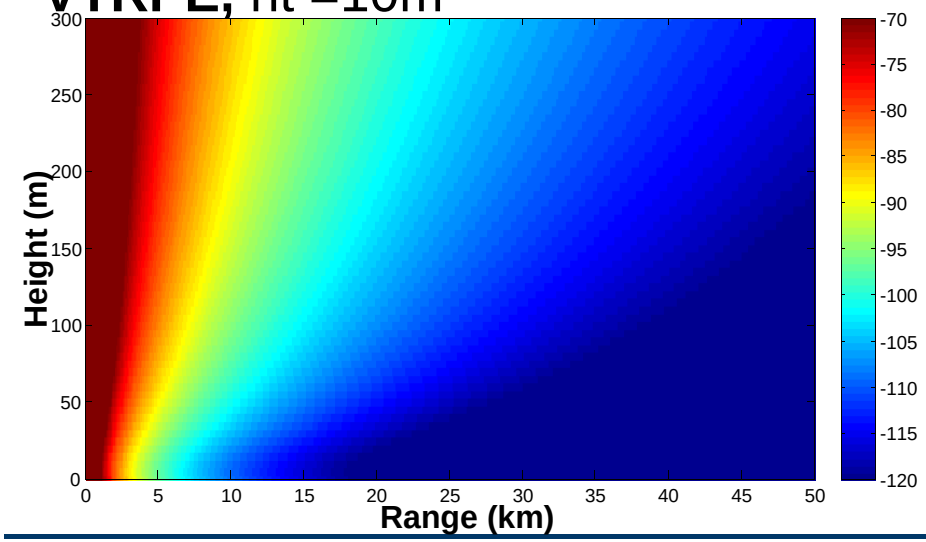
  - Future modeling work
    - Site specific propagation modeling using VTRPE
    - Measurements to refine models
- Summary
- Backup and Additional Information

VTRPE* vs GRWAVE Test Case
(*V*ariable *T*errain *R*adio *P*arabolic *E*quation)

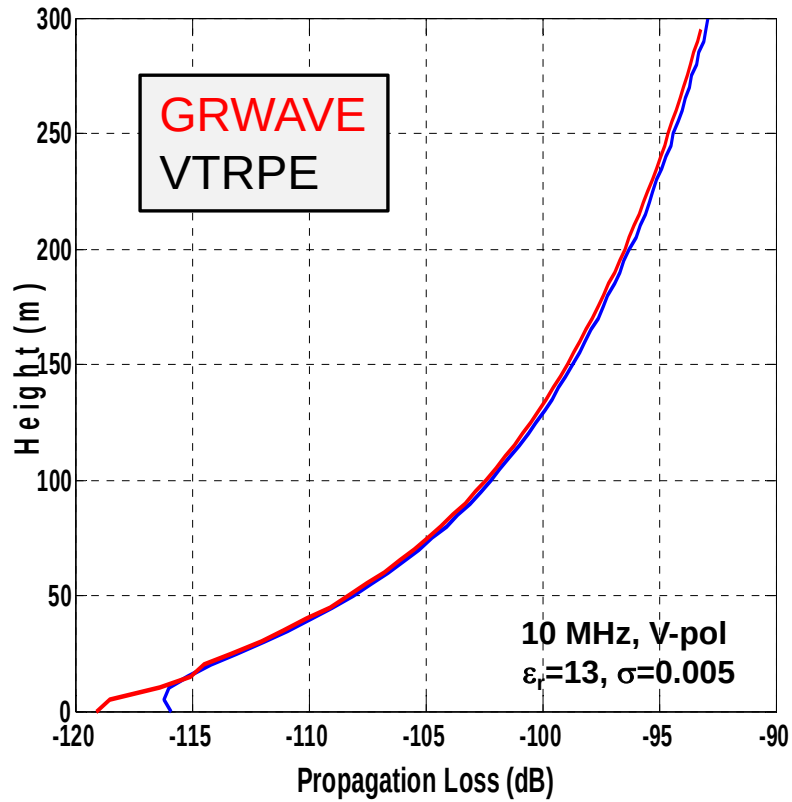
GRWAVE, ht =10m



VTRPE, ht =10m



Propagation Loss vs Height at Range of 15 km



*** Ryan, Frank J., User's Guide for the VTRPE Computer Model, NOSC, San Diego, CA, October 1991**

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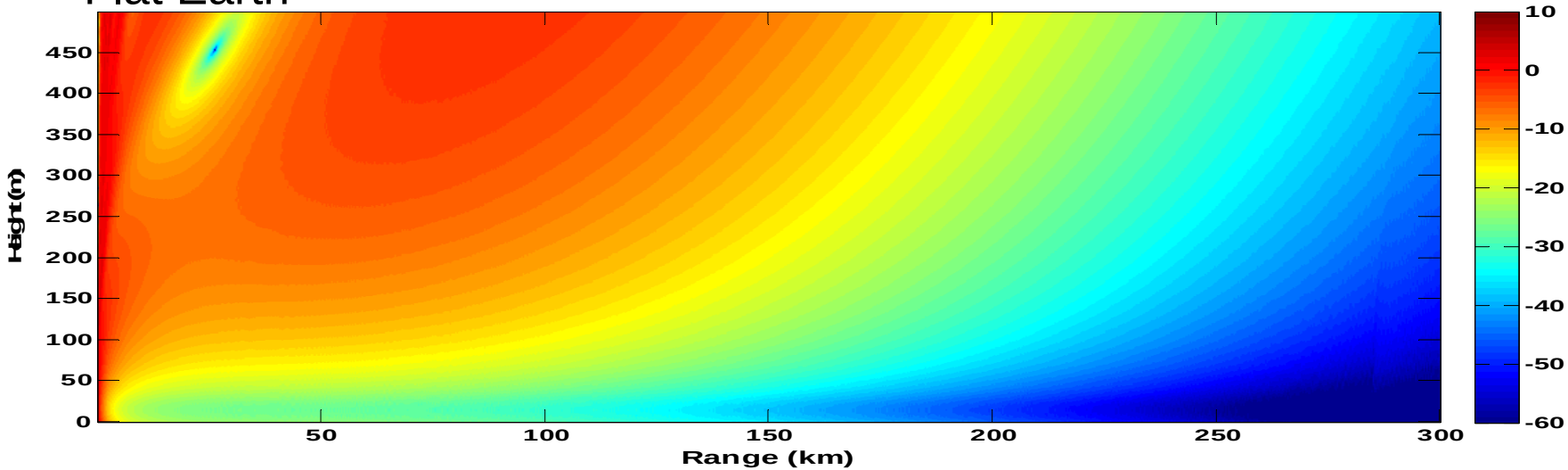
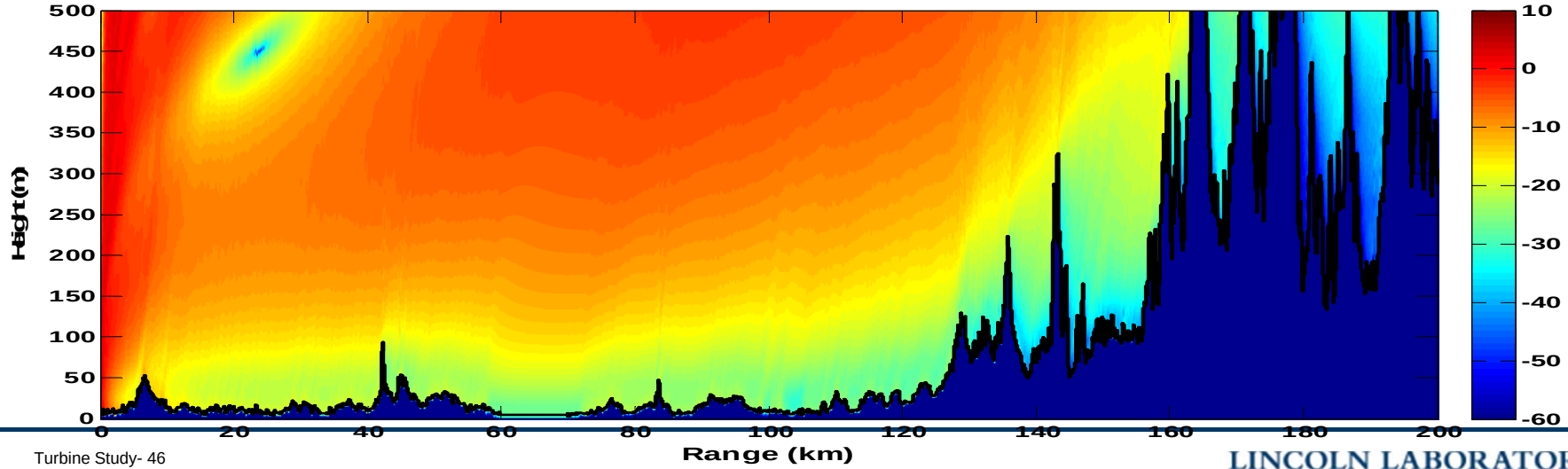
VTRPE Runs for Flat Earth and Variable Terrain

Flat Earth



Variable Terrain



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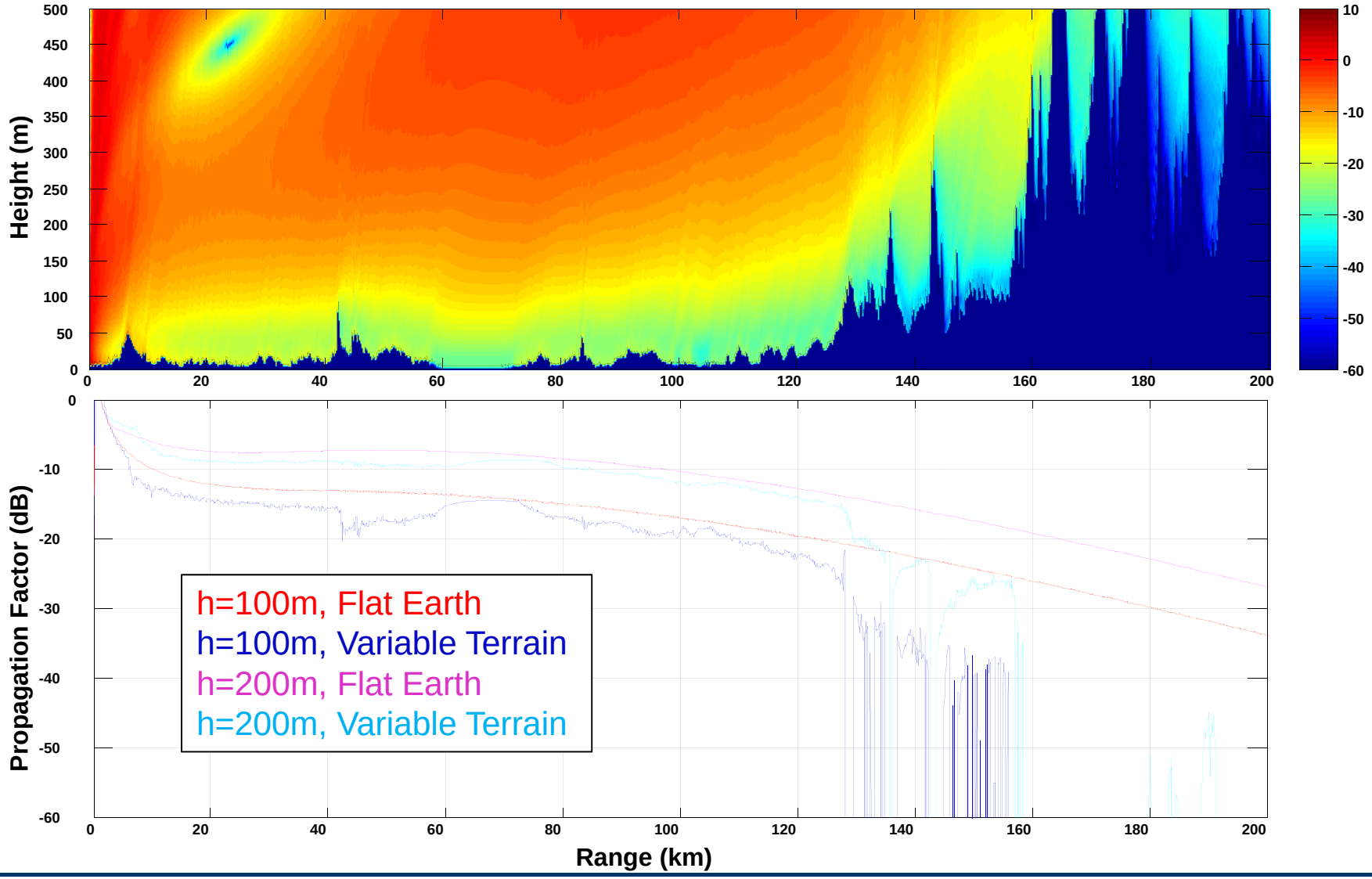
VTRPE: Flat Spherical Earth vs Variable Terrain



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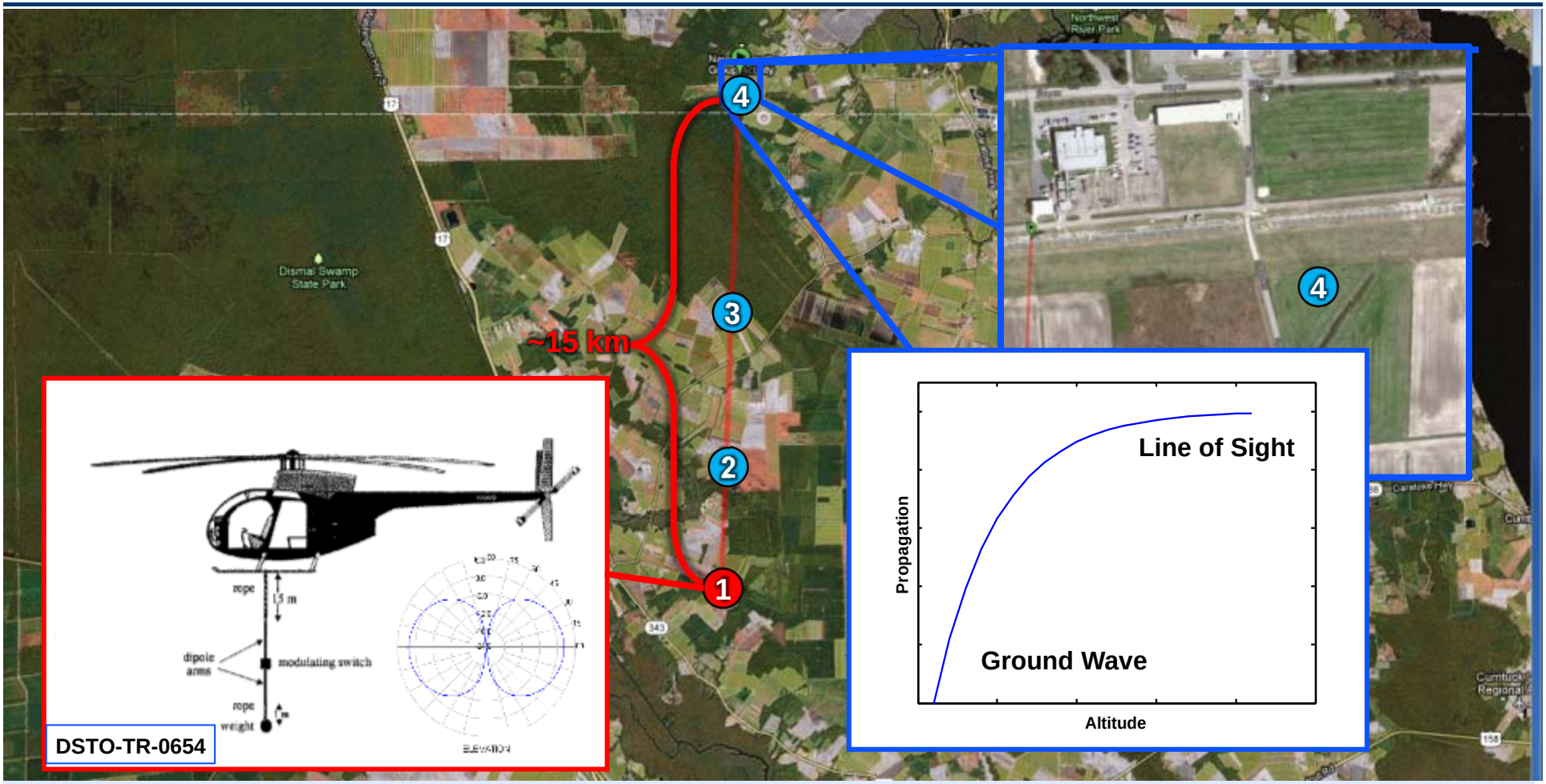
Wind Turbine Scattering Measurements to Verify Models

- **Objective:**
  - **Calibrated EM field measurement of HF propagation loss, wind turbine scattering cross section and modulation spectrum**
  - **Validate models of wind-turbine scattering, ground wave propagation, and spectral modulation on both Tx or Rx signal**

- **Various measurement approaches**
  - **Radar measurement by leverage ROTHR transmitter and or receiver**
  - **Radio transmission measurement with dedicated transmitter and receiver equipment**

Notional Testing Scenario

Use Helicopter to Measure Propagation from LOS to Ground



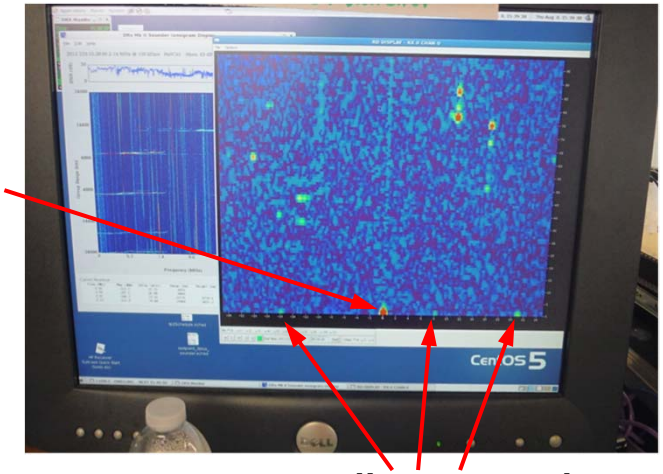
Helicopter measures propagation factor from Line-of-Sight (LOS) altitudes down to the ground. LOS portion of flight removes calibration uncertainties related to ground-based monopole antennas mounted over imperfect ground planes.

Recent LL Test Using a Helicopter-Borne Transmitter

August 2013

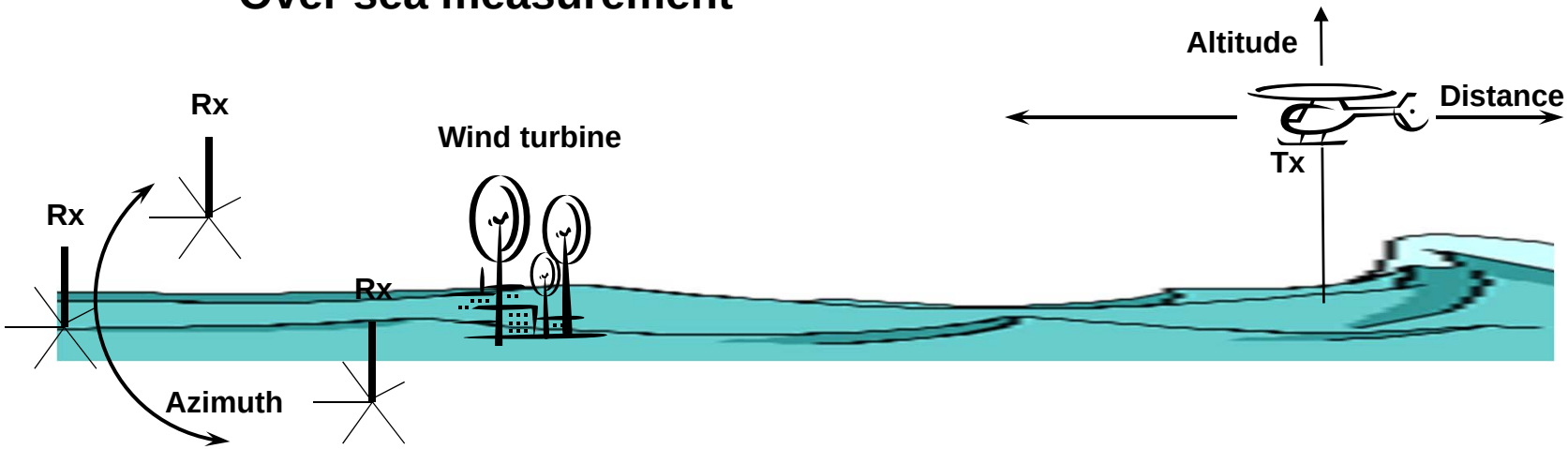
Low-power Transmitter in Helicopter

Receiver on Ground

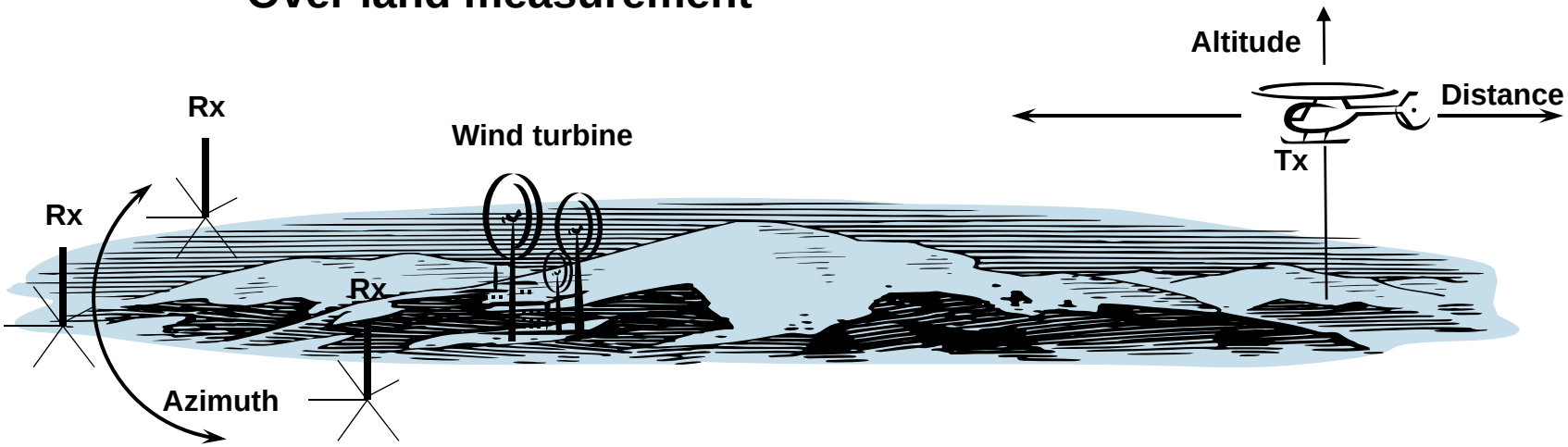


Turbine Experiment with Helicopter-Borne Transmitter

Over sea measurement

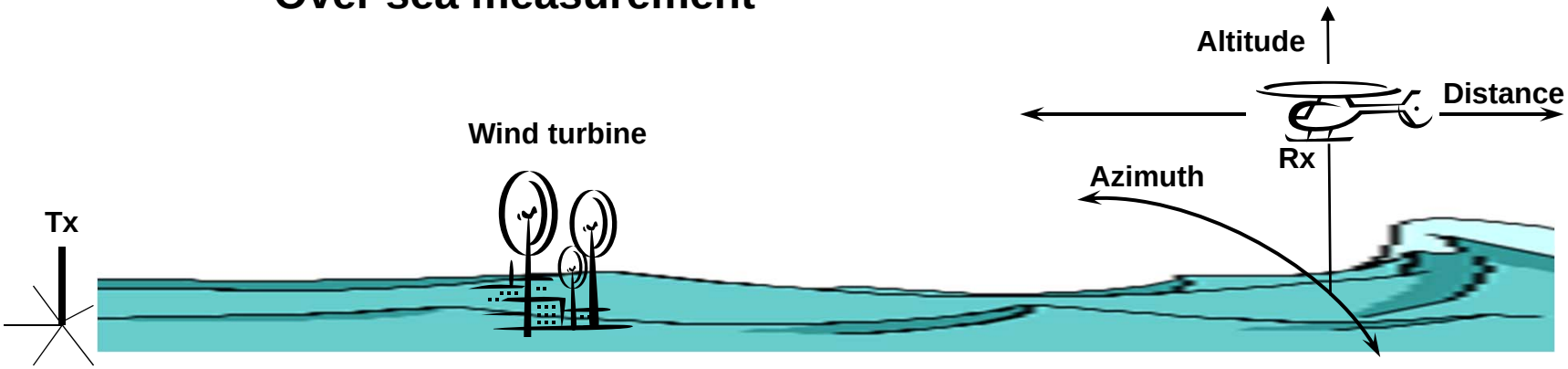


Over land measurement

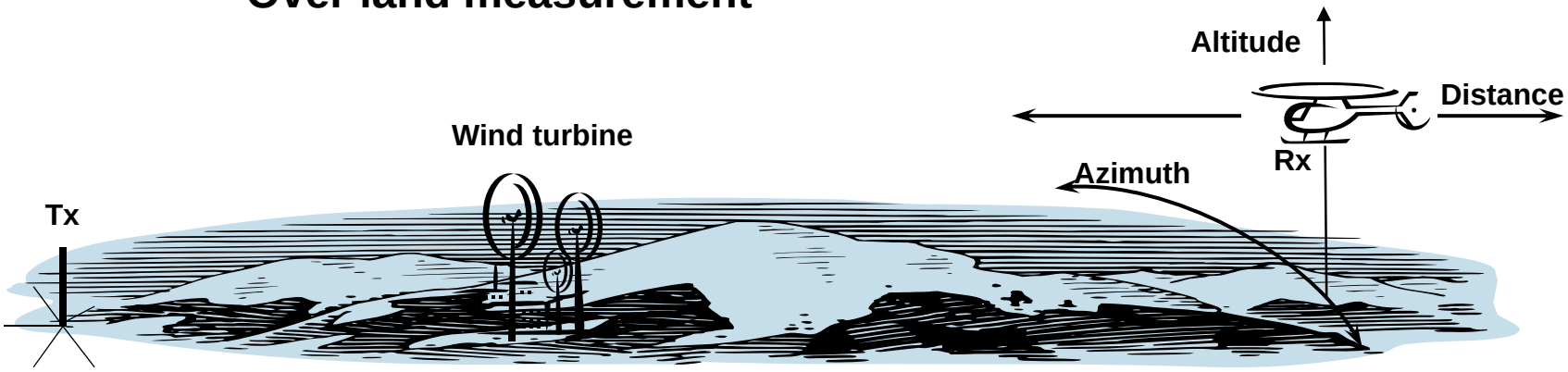


Turbine Experiment with Helicopter-Borne Receiver

Over sea measurement

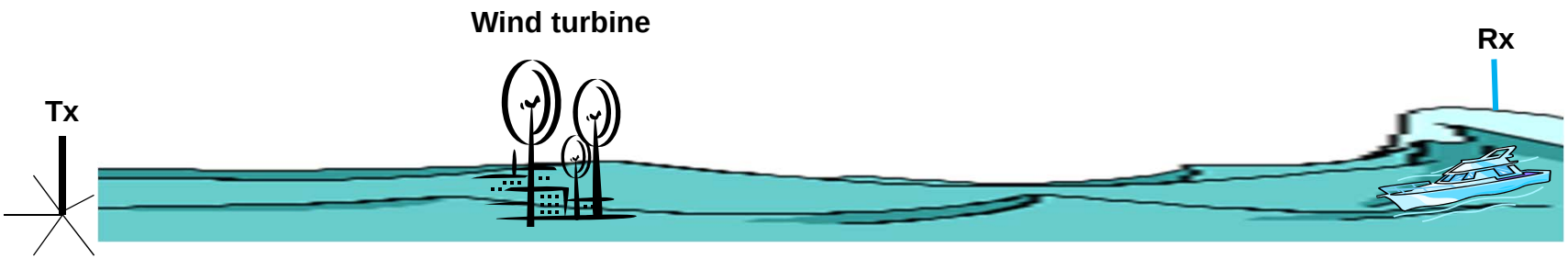


Over land measurement



Turbine Experiment With Surface Vehicle-Based Receiver

Over sea measurement



Over land measurement

Summary

- Wind Turbine model developed
  - Matlab – NEC 4.2 based exploits parallel processing to compute 64 rotation angles simultaneously
- Model used with radar parameters to generate Doppler signatures of wind turbine modulated clutter
- A great deal of effort was expended to validate modeling
  - Propagation, RCS, antennas, and NEC models evaluated and understood
    - Multiple approaches used including hand calculations
  - Limited "final" runs were performed
- Model used to estimate changes to standoff requirements based on wind direction
  - Significant reductions in standoff predicted vs wind direction
- More work is required including measurements to verify models

Backup and Additional Information

Wind Farm Study

Statement of Work

- **Objectives:**
  - Evaluate wind-turbine interference and clutter modulation at HF
  - Assess impacts of wind farm siting on ROTHR operations
  - Recommend wind-turbine interference approaches

- **Scope of efforts: 3 staff-months study**

- **Tasks:**

  1. Review relevant literature
  2. Electromagnetic modeling at HF of wind turbine scattering and ground wave propagation, develop and test computation tools. This model will be capable of rotation and arbitrary angle orientation
  3. Investigate Doppler modulation signatures of wind turbines and their dependence on wind direction, explore interference mitigation approaches
  4. Develop radar signal and system model, evaluate wind-turbine interference to ROTHR, assess effects of siting, geometry, and wind direction

- **Deliverables: briefing of study results**

Study Plan

1. **Develop EM computational tools to model wind-turbine interference**
   1. RCS at HF of wind blades as function of frequency, viewing geometry (aspect at selected elevation angles) and rotational angles
   2. Time series of interference as function of wind-blade rotation
   3. Start with analytic solutions of long wires and supplements with accurate numerical modeling of actual blade structures

2. **Generic OTH propagation modeling**
   1. Nominal HF sky wave propagation in one (and < a few) scenarios
   2. Use available tools such as NEC and GRWAVE to model attenuation ground wave propagation and its dependence on frequency and stand-off distance

3. **Implement ROTHR radar signal and system model**
   1. Investigate wind-farm clutter modulation level and spectra
   2. Assess wind-farm impacts on ROTHR operations and performance such as effects of stand-off distance, size, lay-out, and wind

- **Explore wind-farm interference mitigation approaches, define processing algorithms**

Literature Review (1 of 5)

ROTHR-specific

- ROTHR Program Office, "Comprehensive Modeling Analysis for Stand-Off Requirements of Wind Turbines from Relocatable Over The Horizon Radar (ROTHR) Systems," Executive Report II, Version 2.0, RPO-TR-WF-0712-001, June 2012.
- ROTHR Program Office, "Stand-Off Requirement of Wind Turbines from Relocatable Over The Horizon Radar (ROTHR) Systems," Executive Report, July 2011.
- S. Rodriguez, R. Jennett, J. Bucknam, "Wind turbine Impact on High Frequency Skywave Radar (Initial Assessment)," NRL Tech Report NRL/MR/5320-11-9334, September 30, 2011. Distribution Statement C: Distribution authorized to U.S. Government agencies and their contractors.
- S. Rodriguez, B. Root, "Wind turbine Impact on high Frequency Radar (Line-of-Sight and Skywave Measurements) ," *Proc. Tri-Service Radar Symp.,* TSR-2011V1TP61, 1 June 2011. Distribution Statement C: Distribution authorized to U.S. Government agencies and their contractors.

Literature Review (2 of 5)

Full-size Turbine Measurements

Microwave

- B. Kent, K. Hill, A. Buterbaugh, G. Zelinski, R. Hawley, L. Cravens, T. Van, C. Vogel, and T. Coveyou," Dynamic radar cross section and radar Doppler measurements of commercial General Electric windmill power turbines, part I: Predicted and measured radar signatures," *IEEE Antennas Propag. Mag.*, vol. 50, no. 2, pp. 211-219, Apr. 2008.
- A. Buterbaugh, B. Kent, K. Hill, G. Zelinski, R. Hawley, L. Cravens, T. Van, C. Vogel, and T. Coveyou," Dynamic radar cross section and radar Doppler measurements of commercial General Electric windmill power turbines, part 2: Predicted and measured Doppler signatures," *IEEE Antennas Propag. Mag.*, vol. 50, no. 2, pp. 211-219, Apr. 2008.
- J. Browning, B. Wilson, J. Burns, B. Thelen, "Wind Farm Radar Interference Characterization and Mitigation (wricm): Initial Data Analysis Results," *Proc. of Tri-Service Radar Symp.,* TSR-2010-TA06, 12 July, 2010.

HF

- L. Wyatt and A. Robinson, "Wind farm impacts on HF radar current and wave measurements in Liverpool Bay," *Proc. OCEANS 2011*, Spain, IEEE, 6-9 June 2011, pp. 1-3.

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Scale-model Measurements

Microwave

- A. Naqvi, S. Yang and H. Ling, "Investigation of Doppler features from wind turbine scattering," *IEEE Antennas Wireless Propagat. Lett.*, vol. 9, pp. 485-488, 2010.

- A. Naqvi, N. Whitelonis, H. Ling, "Doppler features from wind turbine scattering in the presence of ground," "*Progress in Electromagnetics Research Letters*," vol. 35, pp. 1-10.

- F. Kong, Y. Zhang, R. Palmer, and Y. Bai, "Wind turbine radar signature characterization by laboratory measurements," *Proc. of RADAR 2011,* pp.162-166, 23-27 May, Kansas City, MO, IEEE.

- Y. Zhang, et al., "Using scaled models for wind turbine EM scattering characterization: Techniques and Experiments," *IEEE Trans. Instrum. Meas.,* vol. 60, no. 4, pp. 1298-1306, Nov. 2010.

Literature Review (4 of 5)

Simulations and Analysis

Study

- **M. Brenner, et al., "Wind farms and radar," JASON Program Office, The MITRE Corporation, McLean, VA JSR-08-125, 2008.**
- **Audrey Durmanian, et al., "Wind Turbine RCS Modeling and Validation", The Applied Computational Electromagnetics Society, April 2011, presentation at Williamsburg, VA and conference paper published online (ACES 2011 Conference – Williamsburg, VA, Volume: Topics in Radar Scattering), MIT LL.**
- **J.K. Jao, C. Ho, P. Jardin, M. Yamaguchi, and P. Monticciolo, "FORESTER GMTI Processing and Performance Test Results of Target Detection and Signature Data Exploitation," 56th 2010 Tri-Service Radar Symposium, Orlando, Florida, 21 – 25 June, 2010."**

Simulation

- **L. Rashid and A. Brown, "RCS and Radar Propagation Near Offshore Wind Farms," *Proc. IEEE Antennas and Propagation Conf.*, Honolulu, HI, 2007, pp 4605-4608.**
- **D. Jenn and C. Ton, "Wind turbine radar cross section," *Int. Journal of Antennas and Propagation*, Vol. 2012, Article ID 252689, 2012.**
- **C. Teague and D. Barrick, "Estimation of wind turbine radar signature at 13.5 MHz," *Proc. of IEEE OCEANS Conf.*, Virginia Beach, VA, 2012.**

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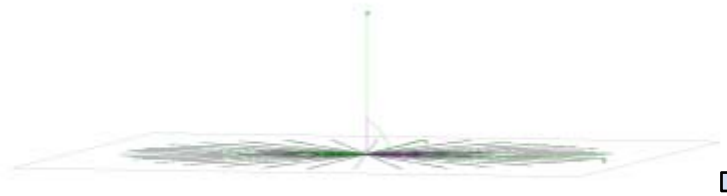
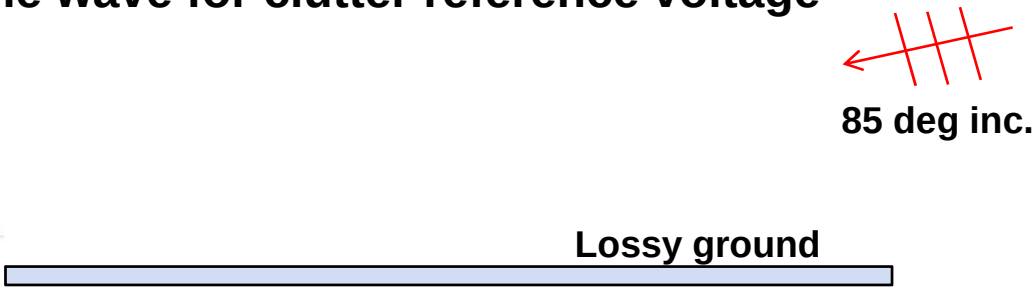
Propagation

- N Maslin, *HF Communications, A Systems Approach*, Plenum Press, New York, 1987
- S. Rotheram, "Ground-Wave Propagation Part 1: Theory for Short Distances," IEE Proceedings, October 1981
- S. Rotheram, "Ground-Wave Propagation Part 2: Theory for Medium And Long Distances and Reference Propagation Curves," IEE Proceedings, October 1981
- Rec. ITU-R P.368-7, "Ground-wave Propagation Curves For Frequencies Between 10 Khz And 30 Mhz" The ITU Radiocommunication Assembly, 1992
- E. Miller, et al., "Radar cross section of a long wire," IEEE Trans AP, May 1969

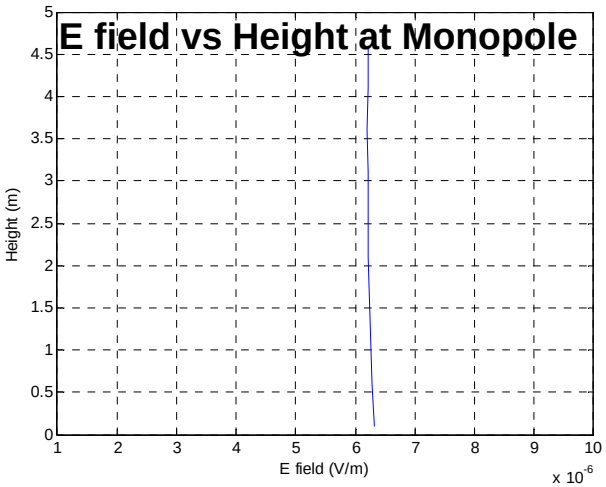
Use NEC to Determine Reference Voltage and Effective Antenna Height

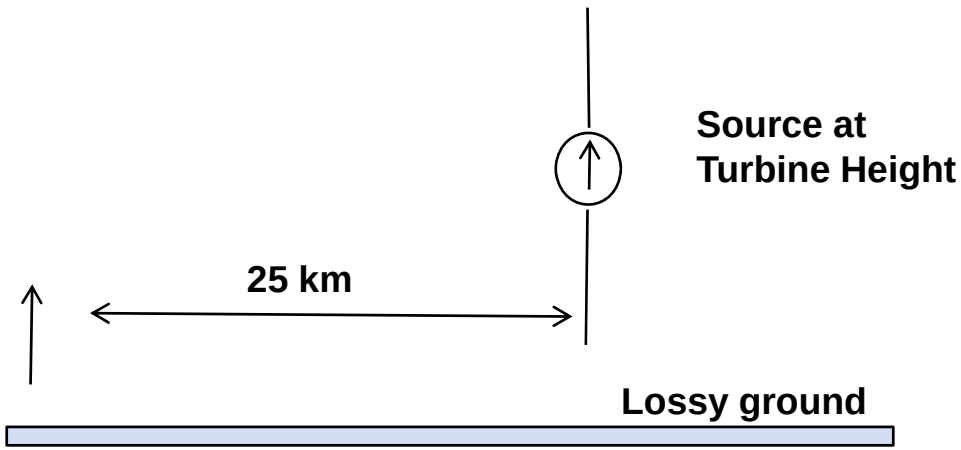
1. Excite monopole with a plane wave for clutter reference voltage





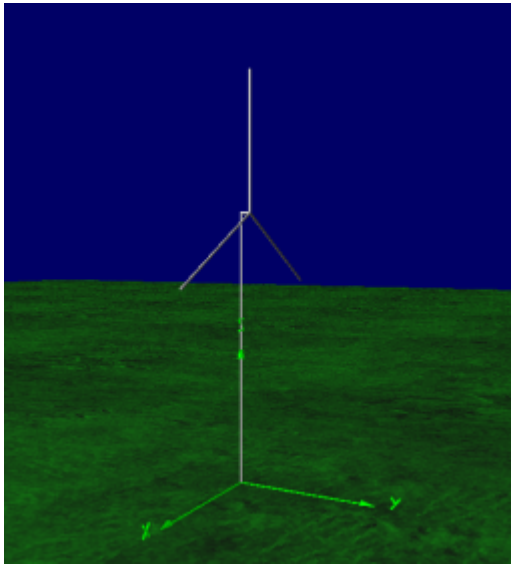
2. Determine effective antenna height V=hE for turbine scattered signal





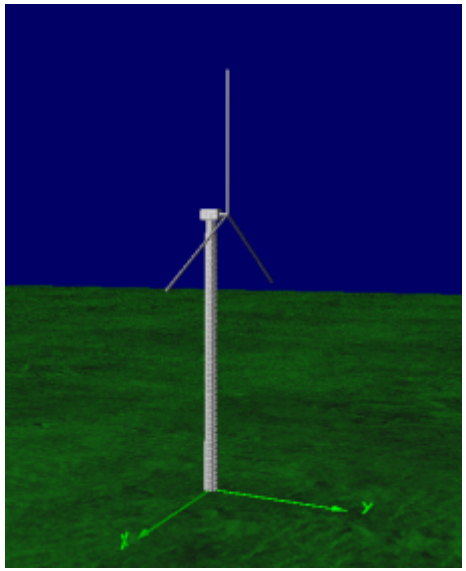
Reference Voltage due to distant clutter signal and effective antenna height from scattered signal required for NEC based 2-step interference solution

Wind Turbine NEC Models



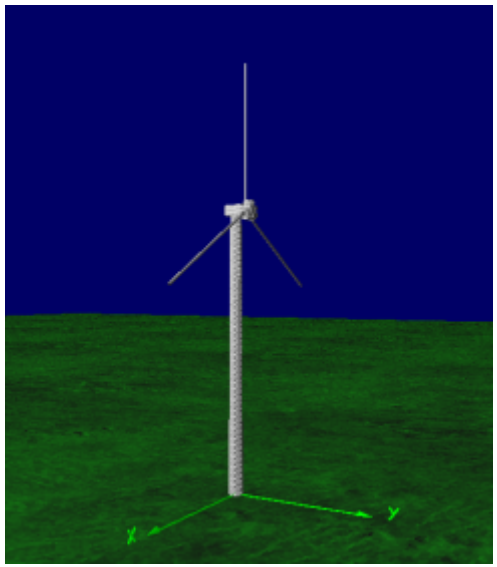
5-Wire Tower

254 segments



Full Tower

6673 segments



Full Tower & Hub

6844 segments