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Beam Propagation Model Selection for Millimeter-Wave Directed Energy Weapons (Presentation)

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Beam Propagation Model Selection for Millimeter-Wave Directed Energy Weapons

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Abstract

We consider low complexity beam propagation models of high powered, millimeter wave (95 GHz) systems. The goal is to achieve reasonable modeling fidelity with minimal compute power, allowing for rapid sampling in large parametric trade space studies. One model under consideration is the relatively simple Fraunhofer or "far field" (FF) approximation which is commonly used in radar and high powered microwave systems. However at the frequency of interest, operational ranges for these systems can fall within the Fresnel zone where the assumptions of the FF approximation are violated. As such we also construct a near field (NF) propagation model based on the field equivalence principle. This model is necessarily more complex than the FF approximation, but is considerably less compute-intensive than full-wave solutions. We compare incident power estimates from the NF and FF models for fixed focus and variable focus millimeter wave systems, showing that the models disagree primarily at ranges below the focal range as expected. Hence in this regime, we expect that the NF model to be the most appropriate. At the focal range and beyond, the models give similar results, suggesting that the FF approximation may be sufficient for characterizing incident power near the focal point, even within the Fresnel zone.

Keywords: Millimeter-Wave; Non-Lethal Weapons; Computational Electrodynamics; Near Field Modeling

1. Background

Modeling and Simulation (M&S) can be used to explore the design trade space of directed energy weapons. M&S can be particularly helpful when that trade space is influenced by a large number of parameters and when acquiring field data to explore those parameters requires a large amount of resources. One example involves the Active Denial Technology (ADT) system, a non-lethal, counter-personnel, directed energy weapon that outputs high powered, millimeter wave electromagnetic energy for crowd control, patrol/convoy protection, and perimeter security [1]. Figure 1 shows a photograph of a current ADT demonstrator (left) and a conceptual drawing of a future iteration of ADT (right).

Figure 1. A photo of an ADT demonstrator (left) and a conceptual drawing of a future iteration of ADT under development (right) [1].

The ADT system subjects a targeted individual to short-duration pulses of a focused beam of directed energy operating at a frequency of approximately 95 GHz (3.2 millimeters in wavelength). At this frequency, and within a known range of doses, the energy diffuses approximately 1/64th inch (400 microns) into the skin of the targeted individual, producing no skin damage. Yet the targeted individual perceives an intense burning sensation, potentially strong enough to repel—that is, to compel the targeted individual to immediately flee the beam [1].

ADT systems that are currently under development can be placed into one of two broad categories: fixed- and variable-focus systems. A fixed focus system (e.g. Figure 1a) combines a high power source with a fixed-focus reflector to achieve operational power densities and spot sizes at relatively long ranges (500 – 1000 m). Variable focus systems (e.g. Figure 1b) are phased arrays of relatively low power emitters with electronic phase control, allowing for dynamic beam-steering and focusing (e.g. the focal point can be varied) [2]. Such systems are expected to deliver an active denial capability in smaller form factors [3].

Like all weapon technologies, the effectiveness of ADT is dependent on both the system design parameters and the target properties. System design parameters include the ADT frequency and output power, among others. Target properties include the targeted individual's skin reflectivity, thermal conductivity, specific heat capacity, density of heat-sensitive neural endings, pain perception thresholds, and motivation, to name a few. Simultaneous exploration of all of these parameters via M&S requires several different model components—some to model the ADT system's output energy, and others to model the targeted individual's physiology, cognition, and behavior. Together, these components can be used to rapidly test hypotheses about how changes to the ADT system design will ultimately lead to changes in the ADT system effectiveness. However, running such a large model can be computationally expensive and therefore each individual component must be as low-intensive as possible.

In this paper, we focus on only the first component—that which simulates the propagation of the ADT beam through the environment to the targeted individual. We explore two different computational models to determine for which situations each model has the necessary balance of fidelity versus computational intensity:

- The first model uses the simple Fraunhofer approximation, also known as the far field (FF) approximation, that is common in radar and high powered microwave (HPM) applications. This approximation is simple and is not computationally intensive. However, operational ranges for high powered, millimeter wave systems like ADT often fall well within the Fresnel region where we cannot assume that the electromagnetic fields are purely diffractive—thus this approximation may not provide the necessary fidelity for all situations.
- The second model is a near field (NF) extension of the FF approximation where the system is approximated by a discrete array of radiators. This approximation is slightly more complex-- it is more computationally intensive but may provide improved fidelity for some situations.

We compare the outputs of our two computational models for both a fixed- and variable-focus millimeter wave system to see in which situations they differ. We also validate our models by comparing their outputs to experimental measurements taken with the variable-focus system. This paper summarizes our findings.

2. Propagation Models

A. Far Field Model

The FF approximation, models the radiated field as a spherical wave front emitting from the phase center. Hence the electric field strength $\boldsymbol{E}$, at position $\boldsymbol{r}$, from a point source located at the origin is estimated by the simple expression:

$$\boldsymbol{E}(\boldsymbol{r}) = \sqrt{2\eta_0 P_{in}}\frac{e^{-jkr}}{4\pi r}\boldsymbol{f}(\hat{\boldsymbol{r}}) \tag{1}$$

where $j = \sqrt{-1}$, $k = 2\pi/\lambda$ is the wavenumber, $r = |\boldsymbol{r}|, \hat{\boldsymbol{r}} = \boldsymbol{r}/r$, P_{in} is the input power, $\eta_0 = \sqrt{\mu_0/\epsilon_0}$ is the impedance of free-space, and $\boldsymbol{f}(\hat{\boldsymbol{r}})$ is the vector field pattern of the radiating source in the direction of the point of interest [4]. The field pattern is a characteristic of the radiating system and can be estimated by geometrical considerations or by direct measurement. In our particular ADT application, we approximate the field pattern by treating the system as a phased array of uniform aperture antennas, each at a position $\boldsymbol{r'}_{\boldsymbol{i}}$ relative to the phase center (assumed to be at the origin) and $i = 1, 2, \dots N$ where N is the number of elements:

$$\boldsymbol{f}(\hat{\boldsymbol{r}}) = \frac{1}{N}\sum_{i=1}^{N} e^{jk r'_i \cdot \hat{r}}\boldsymbol{f_u}(\hat{\boldsymbol{r}}) \tag{2}$$

where $\boldsymbol{f_u}$ is the vector field pattern of a single source, which we assume to be the same for each element. The summation in the equation is known as the "antenna factor" [4]. Note that the expression in Equation 2 is independent of range. The appeal of the FF approximation is that it is simple to calculate and thus computationally efficient, with many of the complexities of the system reduced to determining the field pattern function with respect to direction.

Typically the FF approximation is used to estimate the field strength from simple systems at ranges that are "sufficiently far" from the phase center. The minimum range for this regime is often delineated by the "far field range" given by $R_F = 2D^2/\lambda$, where D describes the length scale of the radiating source [4]. The region below this range is often called the Fresnel region or the "near-field." For ADT systems operating at 95 GHz, R_F can range between 600 – 3000 m, which could be well beyond operational range. Thus the FF approximation may not provide the necessary fidelity because the operational ranges may not be "sufficiently far" enough from the phase center.

B. Near Field Model

We can extend the FF approximation by first approximating the millimeter wave system as a collection of point sources, taking the FF approximation for each, and then coherently summing the contributions of each source for a given point of interest. If the locations of the point sources are denoted by $\boldsymbol{r'}_{\boldsymbol{i}}$, for $i = 1, 2, \ldots N$, then the extended approximation for the electric field strength at $\boldsymbol{r}$ is given by:

$$\boldsymbol{E}(\boldsymbol{r}) = \sum_{i=1}^{N} \sqrt{2\eta_0 P_i}\, a_i \frac{e^{-jk|r - r_i'|}}{4\pi|\boldsymbol{r} - \boldsymbol{r}_i'|} \boldsymbol{f}\left(\frac{\boldsymbol{r} - \boldsymbol{r}_{\boldsymbol{i}}'}{|\boldsymbol{r} - \boldsymbol{r}_{\boldsymbol{i}}'|}\right) \tag{3}$$

where P_i is the effective output power of the $\boldsymbol{i}$-th source and a_i is a complex (unit-less) weighting factor that accounts for differences in phase between the sources. Here again, we assume that each element has the same vector field pattern $\boldsymbol{f}$. Also note that in contrast to Equations 1 and 2, the terms in the summation depend on the range.

In the case of a phased array system, application of Equation 3 is straightforward if the vector field pattern is known. For a reflector/aperture based system, we can also use Equation 3 by first approximating the overall system as a phased array of point sources. We do so by using the well-known "field equivalence principle[1]" in classical electromagnetics to represent reflector/aperture based systems as "fictitious" current sources on a 2D surface (typically the aperture plane), then discretizing these sources to create an effective 2D phased array. In order to obtain these equivalent sources, we need knowledge of the electric and magnetic fields on the aperture plane. This could be obtained through direct measurement or through high fidelity modeling of the source. For this report, we estimate the fields using the following approximations: 1) the aperture plane is uniformly illuminated and 2) the fields are approximately radiative at the aperture[2]. These approximations lead to the relationship:

$$P_i = \frac{P_{in}\Delta A}{A} \tag{4}$$

where A is the area of the aperture and ΔA is the area of the discrete element. The phase term, a_i, is determined by the phase profile on the aperture. If the aperture is designed to be focused at a position, $\boldsymbol{R_f}$, then a_i is given by:

$$a_i = e^{j\,k\,|\boldsymbol{R_f} - \boldsymbol{r}_i'|} \tag{5}$$

The vector field pattern $\boldsymbol{f}$ is obtained by assuming that each element is approximately a square aperture antenna with approximately radiative fields on the aperture. Adopting the

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[1]For a detailed discussion, see Ref [5-6]

[2] E.g. $\boldsymbol{H_a} = \frac{1}{\eta_0}\hat{\boldsymbol{n}} \times \boldsymbol{E_a}$ where $H_a$is the magnetic field strength, E_a is the electric field strength, $\hat{\boldsymbol{n}}$ is a unit vector normal to the aperture plane, and η_0 is the free space impedance.

coordinate system where the y-axis is normal to the aperture and the x and z axes are along the width and length of the aperture, we obtain the following for the element field pattern:

$$\boldsymbol{f}(\widehat{\boldsymbol{R}}_{\boldsymbol{i}}) = jk\,\sqrt{\Delta A}\,\mathrm{sinc}\left(\frac{k\Delta x\widehat{\boldsymbol{R}}_{\boldsymbol{i}}\cdot\widehat{\boldsymbol{x}}}{2\pi}\right)\mathrm{sinc}\left(\frac{k\Delta z\widehat{\boldsymbol{R}}_{\boldsymbol{i}}\cdot\widehat{\boldsymbol{z}}}{2\pi}\right)$$
$$\left[\widehat{\boldsymbol{R}}_{\boldsymbol{i}}\times\left(\widehat{\boldsymbol{p}}_i\times\widehat{\boldsymbol{R}}_{\boldsymbol{i}}\right)+\ \widehat{\boldsymbol{R}}_{\boldsymbol{i}}\times(\widehat{\boldsymbol{p}}_i\times\widehat{\boldsymbol{y}})\right] \tag{6}$$

where $\widehat{\boldsymbol{p}}_i$is the direction of the electric field at the i-th element (i.e. polarization), Δx and Δz are the lengths of the aperture in the x and z axes respectively and $\widehat{\boldsymbol{R}}_{\boldsymbol{i}} = (\boldsymbol{r}-\boldsymbol{r}'_{\boldsymbol{i}})/|\boldsymbol{r}-\boldsymbol{r}'_{\boldsymbol{i}}|$.

The NF approximation is necessarily more complex than the FF approximation. The additional complexity increases the computational intensity—however, the NF model is still considerably less compute-intensive than full-wave solutions. The additional complexity may also improve fidelity, as we explore below.

3. Model Comparisons

A. Fixed Focus System

We first consider a fixed-focus, 95 GHz system with a nominal output power of 45 kW, an effective aperture size of 2 m × 2 m, and a focal range of 500 m. With these nominal parameters and the assumptions discussed above, we can estimate the incident power density on a target at a position down-range (y), cross-range (x), and elevation (z) relative to the system.

The estimates from the two models on the beam cross-sections are shown in Figure 2 for different target ranges (100 m, 275 m, 500 m). At 100 m (top row), the beam profiles are markedly different. The FF beam profile (left) shows small beam diameters with several visible side-lobes. On the other hand, the NF profiles (right), show a rectangular pattern, reflecting the shape of source aperture. Thinking of this in terms of the geometric optics, the emitted beam has not yet diverged. At 275 m (middle row), the two models show similar peaks, but with the FF beam profile estimating a larger beam spot size. At 500 m (bottom row), i.e. the focal range, the beam profiles are very similar.

This trend with range is more evident in Figure 3 which gives the estimated peak power density as a function of target range. As shown, the FF approximation (orange) shows the $1/R^2$ dependence that diverges at short ranges, as expected. In contrast, the NF approximation (blue) shows a Fresnel peak near 300 m, followed by a roughly $1/R^2$ decay. For targets closer than roughly 300 m, the estimates from the models are significantly different, but as we approach the focal range (500 m) and beyond, the models appear to give similar results. In some sense, this trend in range is as expected – the models give similar results at larger ranges. However the far field range R_F for this case ($2D^2/\lambda$) is roughly 2500 m, suggesting that we are still well within the near field regime.

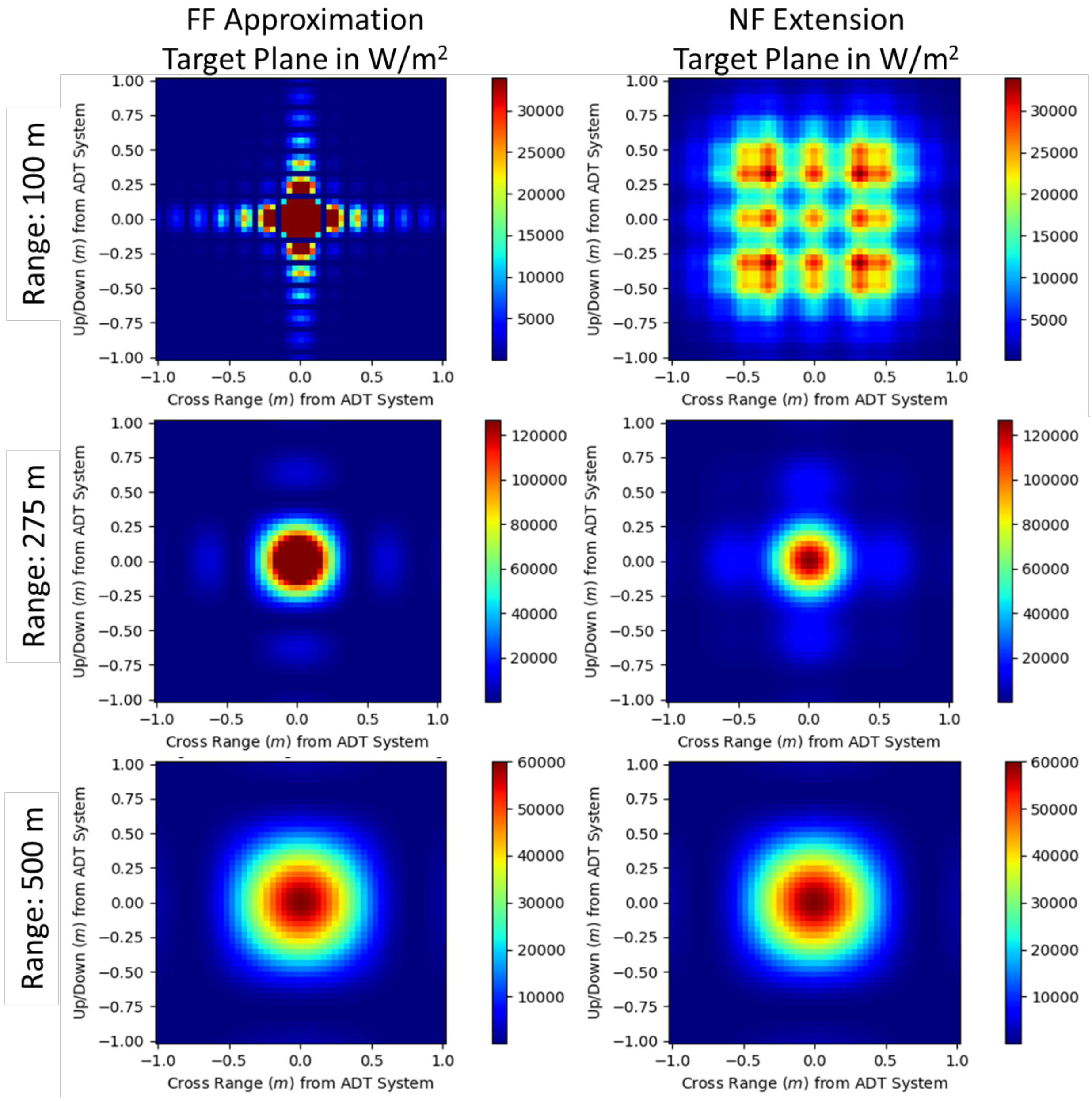

Figure 2: Comparison of the incident beam profiles in the target plane as estimated by our FF (left column) and NF (right column) models at 100 m, 275 m, and 500 m down-range of a fixed-focus system.

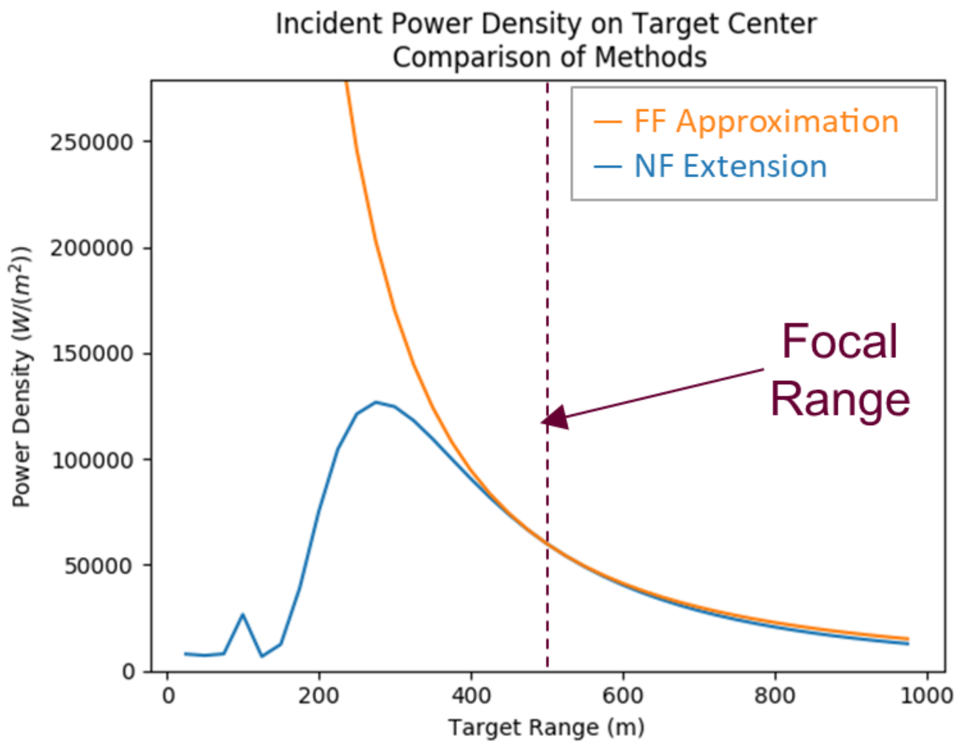

Figure 3: Estimated peak power density incident on target with respect to down-range target distance from a fixed-focus system.

B. Variable Focus System

We now consider a 95 GHz phased array system with a variable focusing capability (i.e. electronic phase control). In particular, we consider a nominal 32 × 256 element array with a nominal aperture size of 1m × 1m and a nominal average element output power of 0.8 W. We also assume that for a given target range, the phases on each element are chosen to focus the beam at the target. In other words, the focal range is always equal to the target range.

The estimates from the two models on the beam cross-sections are shown in Figure 4 for different target ranges (15 m, 40 m, 115 m). The notable feature in the figure is that beam profiles are essentially the same between the models for each range. The consistency between the models is also seen in Figure 5, which gives the estimated peak power density with respect to target range. Here the figure shows that the two models are generally consistent for all ranges considered.

This agreement, however, is only seen near the target position. Figure 6 shows the beam profile in the down-range, cross-range plane (i.e. "bird's eye" view). As expected, the FF estimates (left column) do not vary with range. In contrast, the NF estimates (right column) show differing profiles for each target range (demonstrating the variable focusing). These figures show that the two models are only in agreement near the focal point. R_F in this case is roughly 600 m.

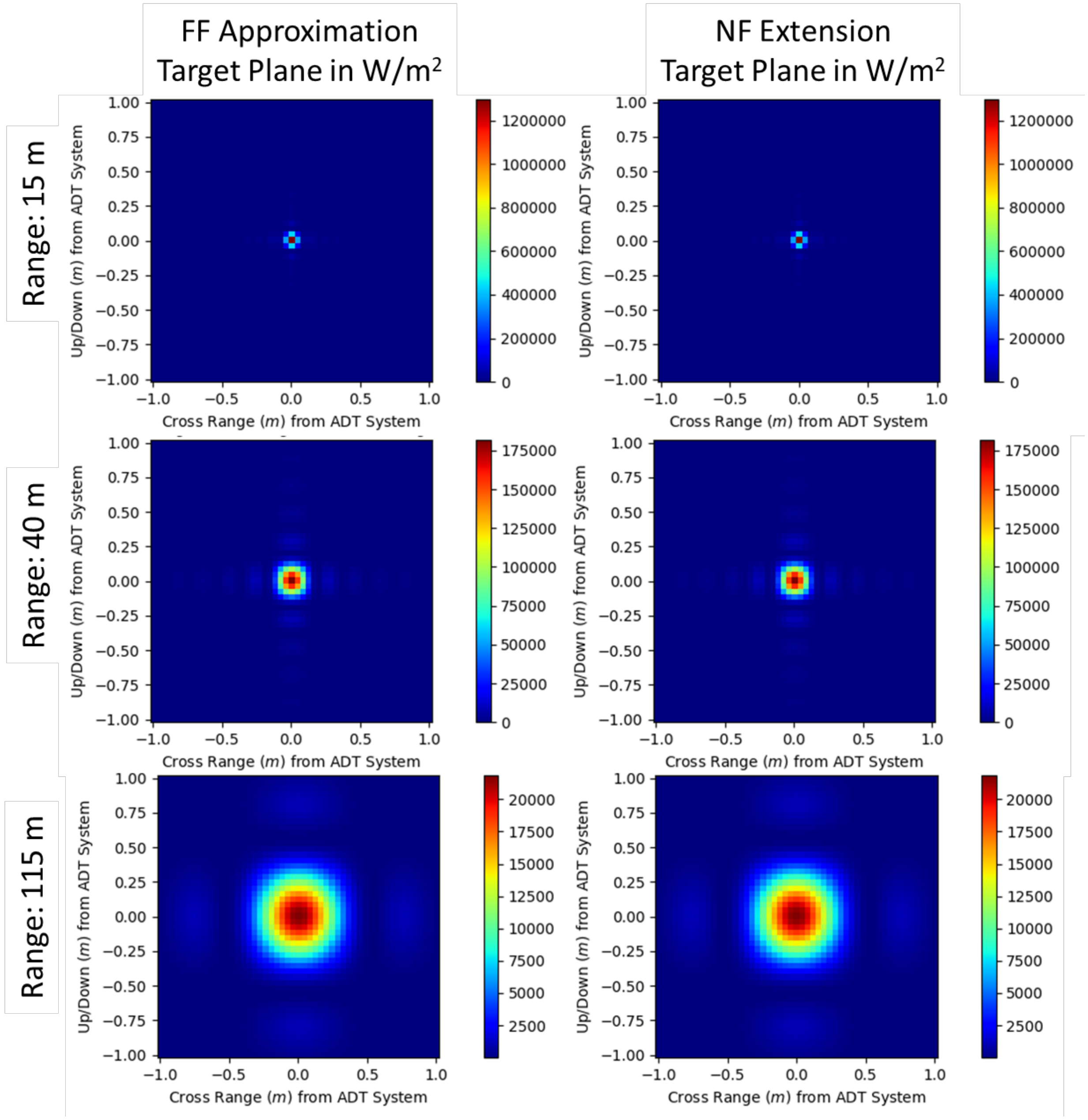

Figure 4: Comparison of the incident beam profiles in the target plane as estimated by our FF (left column) and NF (right column) models at 15 m, 40 m, and 115 m down-range of a variable-focus system.

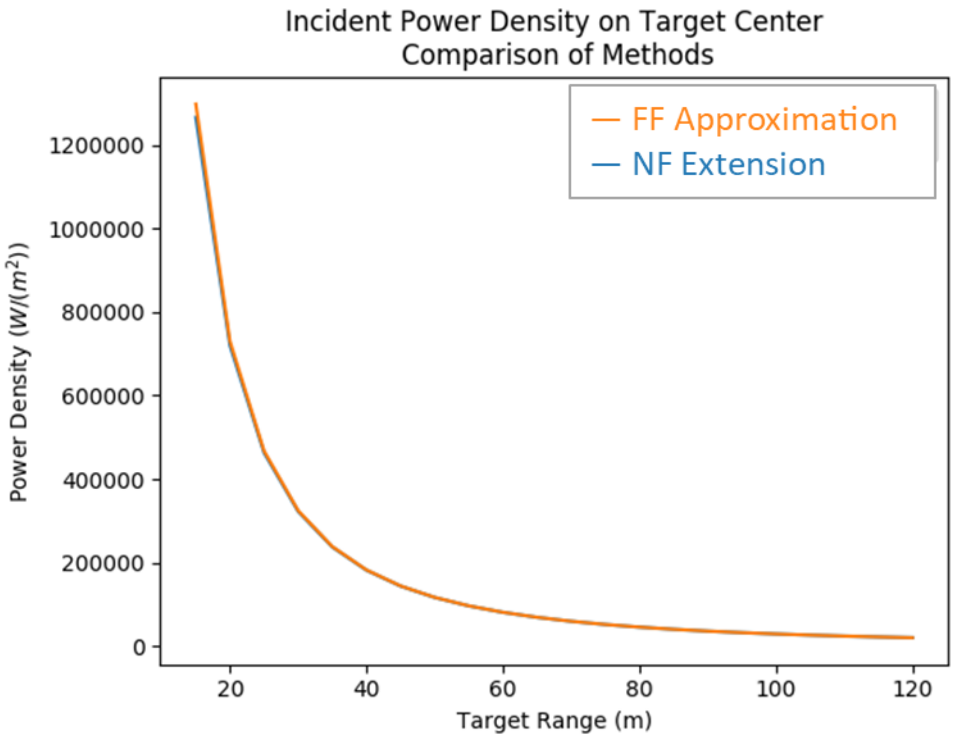

Figure 5: Estimated peak power density incident on target with respect to down-range target distance from a variable-focus system.

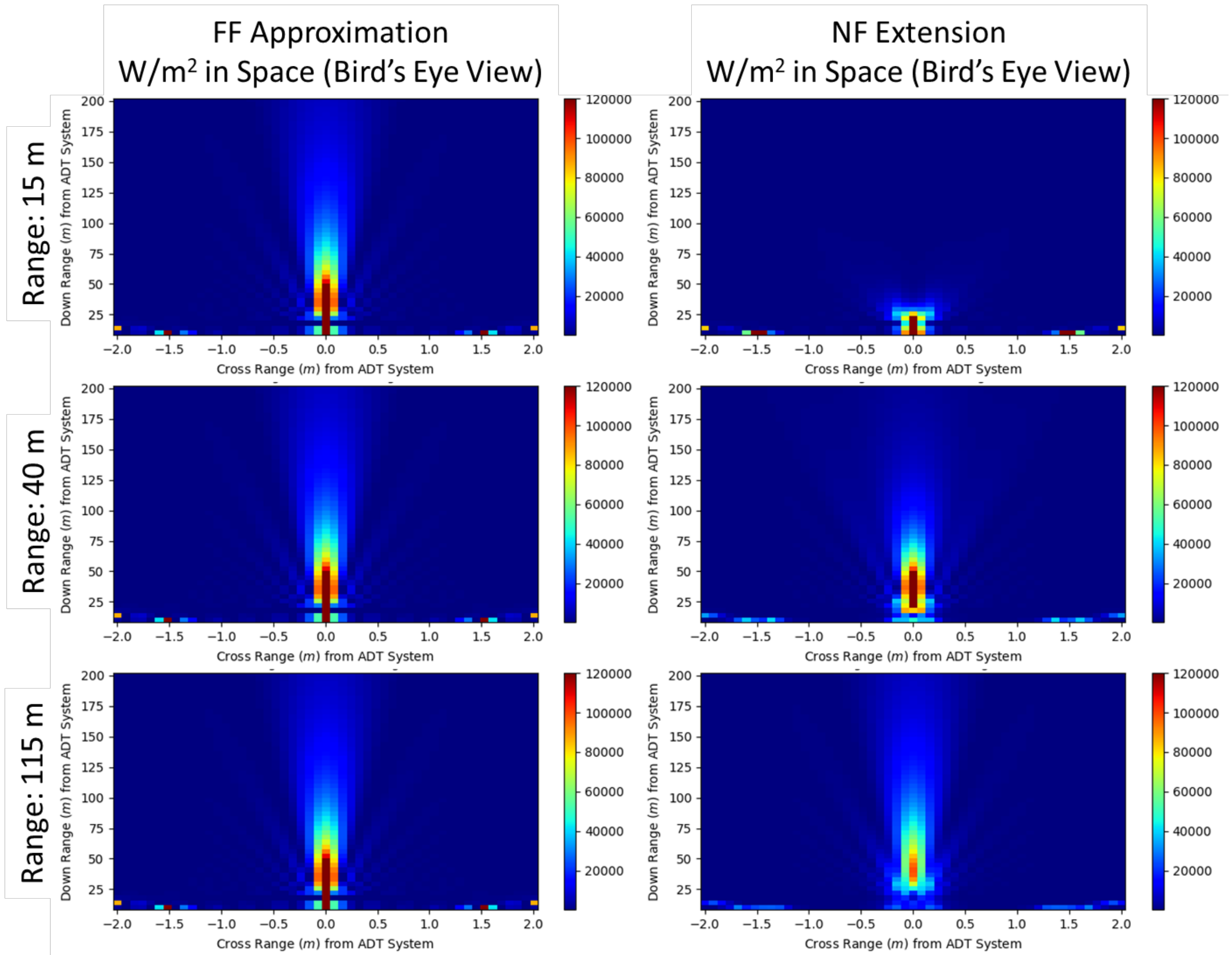

Figure 6: Comparison of the incident beam profiles in the down-range, cross-range plane ("bird's eye" view) as estimated by our FF and NF models at 15 m, 40 m, and 115 m down-range of a variable-focus system.

The essential takeaway from these results is that the FF model provides the necessary fidelity near the focal point of millimeter wave systems. The Fraunhofer approximation is an estimate of the "diffractive fields," which for systems focused at infinity, are expected to dominate at significantly far ranges. In the case of systems with a finite focus, the "ray" description of the fields diverges and the fields are purely diffractive. Hence the Fraunhofer approximation gives a good estimate for the field strengths in this regime.

4. Model Validation

To validate our models, we sought to compare their estimates to experimental measurements. Experimental measurements of a fixed-focus ADT system were not fully available—therefore validation tests are reported here for only variable-focus systems. We should note that the parameters used to validate the model differ from those that are used in the section above. In particular, the variable-focus system under investigation has coarse phase control, meaning that the element phases are controlled in “blocks” where the elements in a block have the same phase [2]. This is modeled as a coarse array where each modeled element represents a block.

Figure 7 compares the peak power density incident on the target estimated by our NF model (×) and FF model (○) versus the experimental measurements (■) reported in Ref [7]. No error bars were reported for the experimental measurements and therefore it is difficult to assess by eye how well the modeled calculations match the measurements. Figure 8, however, shows the error between the peak power density estimates versus the experimental measurements. For short target ranges less than 40 m, the FF model over-estimates the peak power density, differing from the experimental measurements by more than 1 dB. For long target ranges greater than 40 m, however, the FF calculations matched the experimental measurements to within 1 dB. In contrast, the NF calculations matched the experimental measurements to within 1 dB for all target ranges.

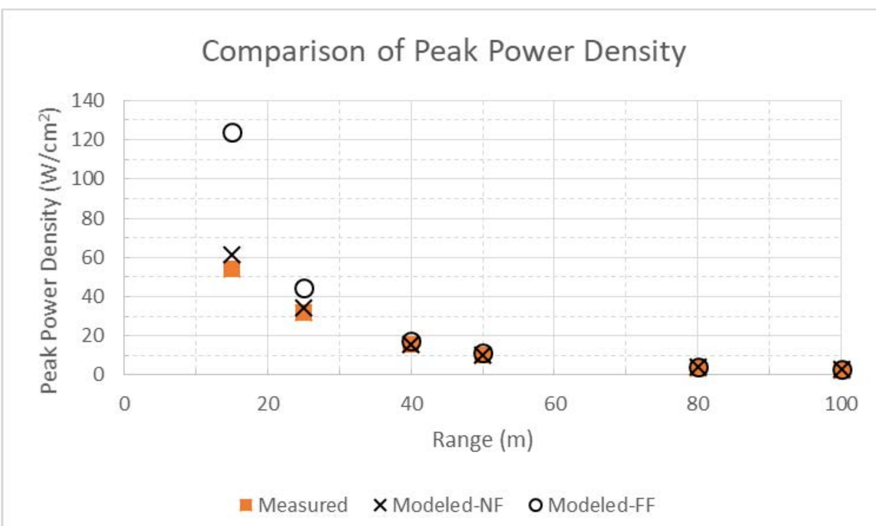

Figure 7. Validation results comparing our NF model (×) and FF model (○) to the experimental measurements (■) reported in Ref [7].

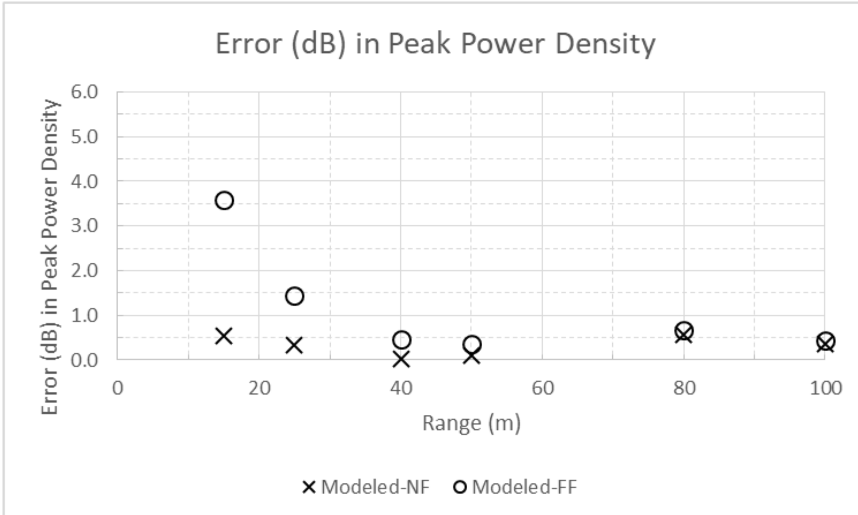

Figure 8. Validation results showing the error between our NF model (×) and FF model (○) versus experimental measurements in Ref [7].

5. Conclusions

We have examined the use of the FF approximation and a NF extension of this method to model beam propagation for high powered, millimeter wave systems designed for ADT applications. We compared the results of these methods for fixed and variable focus systems with operational ranges within the Fresnel region (i.e. less than the far field range). We observed that the two methods generally differ except near the focal point. This result can be understood by noting that near the focal point, diffractive fields are expected to dominate, and the FF approximation is generally reliable in this regime even in the near field. The result does suggest that for systems with a variable focusing capability, the FF approximation may be suitable for estimating power densities on targets.

We also compared the results from the two methods to experimental measurements obtained from a variable-focus system to validate our models. In this comparison, we observed that our NF model is in qualitative agreement with the experimental measurements. However an interesting result from the validation study is that the FF estimates can differ considerably from the NF estimates, in contrast to our results from the comparison study. The likely reason for this is that the system under investigation has coarse phase control by design. As such, the aperture is not perfectly focused. As a result, the fields are not purely diffractive at the desired focal point. The effects of this coarse phase control are most severe at close ranges, but decrease with increasing range. This suggests that there are limits to using the Fraunhofer approximation, even for systems with a variable focusing capability; its suitability depends on the coarseness of the phase control and the range to the target.

The validation results for our NF model are encouraging and suggests that this method has reasonable fidelity for exploring various design trade spaces. Although the NF model is more complex and computationally intensive than the FF model (i.e. on the order of N times more calculations where N is the number of modeled elements), the computational costs are not unreasonable and are considerably less than full-wave solutions. Therefore with the goal of examining ADT effectiveness with respect to a number of factors (i.e. system design, environment, target properties, etc.), we can use the NF model as the first component in a series of models that examines a target’s physiological, cognitive and behavioral response to ADT in an end-to-end framework. Used together, these component models could be a useful tool for assessing how changes in ADT system design can affect the overall effectiveness of ADT in operational scenarios.

6. Acknowledgments

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7. References

[1] JNLWP. 2016, May 11. *Active Denial Technology Fact Sheet*. http://jnlwp.defense.gov/Portals/50/Documents/Press_Room/Fact_Sheets/ADT_Fact_Sheet_May_2016.pdf. Last accessed August 14, 2018.

[2] Brown, K., A. Brown, T. Feenstra, D. Gritters, S. O'Connor, M. Sotelo, N. Kolias, K. C. Hwang, J. Kotce, E. Robinson "7kW GaN W-band transmitter," *2016 IEEE MTT-S International Microwave Symposium (IMS)*, San Francisco, CA, 2016, pp. 1-3.

[3] Robinson, Edward. "Solid State Active Denial Technology Demonstrator Program," *Joint Armaments Conference,* 2012.

[4] Stutzman, Warren L, and Gary A Thiele. 2012. *Antenna theory and design*: John Wiley & Sons.

[5] Balanis, Constantine A. 2005. "Antenna Theory, Hoboken." *New Jersey: John Wiley & Sons, Inc* 8:21-31.

[6] Orfanidis, Sophocles J. 2002. *Electromagnetic waves and antennas*: Rutgers University New Brunswick, NJ

Parker, James et al. “Millimeter Wave Dosimetry Assessment of the Solid-State, Active Denial Technology Device,” *Air Force Research Laboratory*, AFRL-RH-FS-TR-2014-0028, 2014

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Outline

- Background
- System Description
- Propagation Models Overview
- Model Comparison Study
- Validation Study
- Conclusions

Background

- Modeling & Simulation (M&S) are critical tools for **trade studies**
    - Often necessary for evaluating new system designs
    - Alternative to resource-intensive field testing of existing systems

- However the trade space can be large for typical systems

- Typical tradeoff for M&S tools between
    - **Speed**: low compute-intensive models allow for rapid sampling of trade space
    - **Fidelity**: accurate models produce description of underlying phenomenology that generalizes to real world

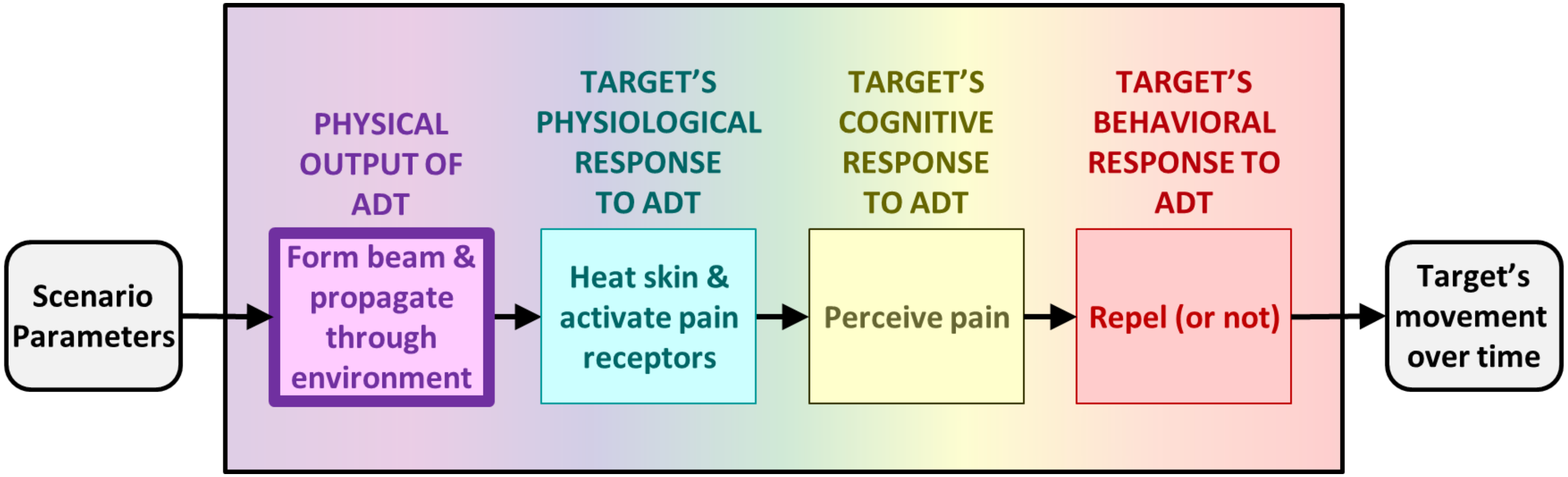
Active Denial Technology (ADT)

- 95 GHz, non-lethal, counter-personnel, directed energy weapon
- Energy diffuses approximately 1/64th inch (400 microns) into the skin of the targeted individual
- With appropriate "dose-on-target," penetrating energy produces a burning sensation without causing skin damage
- The sensation can compel a repel response
- Two types:
  - Fixed focus, reflector based systems
  - Phased array with electronic (variable) steering and focusing

Active Denial Technology Fact Sheet. JNLWP. 2016, May 11. http://jnlwp.defense.gov/Portals/50/Documents/Press_Room/Fact_Sheets/ADT_Fact_Sheet_May_2016.pdf

Assessing ADT Effectiveness

- A target’s response to ADT depends on many parameters – system, environment, skin
- Exploration of this parameter space via M&S requires many models
- We combine models in an end-to-end framework to compare-and-contrast ADT system designs in different military scenarios
- For rapid iteration of hypotheses, we desire models with:
  - Low computational intensity
  - Adequate fidelity
- This study focuses on the first model: **ADT beam formation & propagation**



Study Overview

- Compare two simple approaches for modeling 95 GHz propagation

- **Far-Field (FF) Approximation**
  - Approximate system via $1/R^2$
  - **Pro:** Low computational intensity – simple calculation
  - **Con:** Expected low fidelity – ADT operational ranges often fall in the near-field (Fresnel) region, where the $1/R^2$ approximation is not expected to be valid

- **Near-Field (NF) Extension**
  - Approximate system as discrete array of radiators, then take $1/R^2$ approximation for each
  - **Pro:** Expected improved fidelity in near-field (Fresnel) region
  - **Con:** More computationally intensive – scales by number of radiators

Distribution Statement A: Approved for public release; distribution is unlimited

Modeling ADT

Purpose: Characterize the ADT output power based on parameters that are in the control of the ADT system developers and/or operators

Approach: Field Equivalence Principle

- Represent reflector as fictitious currents on aperture plane
- Fictitious currents are derived from radiated output power *P* and these assumptions:
    - Uniform Illumination on aperture: $|\boldsymbol{E_a}| = \sqrt{2\eta P/area}$
    - Huygens source: $\boldsymbol{H_a} = \frac{1}{\eta_0}\hat{\boldsymbol{n}} \times \boldsymbol{E_a}$
- Discretize the fictitious currents to obtain an effective phased array

Input Parameters for Modeling a *Fixed Focus* System:

- Aperture Dimensions (w × h)
- Downrange Focal Point
- Output Power

Input Parameters for Modeling a *Variable Focus* System:

- Number of Array Elements (w × h)
- Spacing of Array Elements (w × h)
- Average Element Output Power

Propagation Models

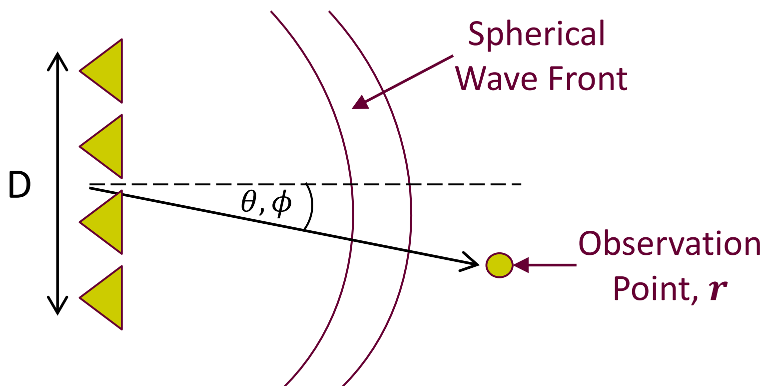
Purpose: Estimate power density incident on target's skin surface (dose-on-target), based on environmental conditions and scenario geometry

Far Field (FF) Approximation:

- Treat array as single point source
- Propagate source's effective radiation pattern to the observation point

$$\boldsymbol{E}(\boldsymbol{r}) = \sqrt{2\eta_0 P_{in}}\frac{e^{-jkr}}{4\pi r}\boldsymbol{f}(\hat{\boldsymbol{r}})$$

where P_{in}: Output power, η_0: Free space impedance, $\boldsymbol{r}$: Observation point, $\boldsymbol{f}(\hat{\boldsymbol{r}})$: Array field pattern

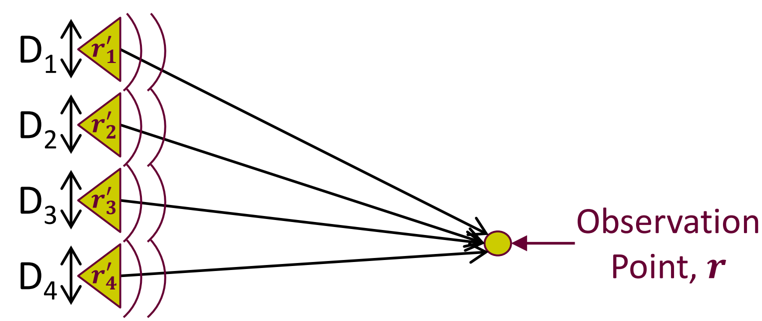


Near Field (NF) Extension:

- Treat array as multiple point sources
- Coherently sum the radiation patterns of each source at the observation point

$$\boldsymbol{E}(\boldsymbol{r}) = \sum_{i=1}^{N}\sqrt{2\eta_0 P_i}\,a_i\frac{e^{-jk|\boldsymbol{r}-\boldsymbol{r}_i'|}}{4\pi|\boldsymbol{r}-\boldsymbol{r}_i'|}\boldsymbol{f}\left(\frac{\boldsymbol{r}-\boldsymbol{r}_i'}{|\boldsymbol{r}-\boldsymbol{r}_i'|}\right)$$

where P_i: Element output power, a_i: Element weighting factor, $\boldsymbol{r}_i'$: Element location



Comparing Modeling Approaches for Fixed Focus ADT Systems (1 of 5)

Parameters used to model ***Fixed Focus*** ADT System:

- Aperture size 2×2 meters
- Focal point 500 meters
- Pulse duration 1 second
- Standard Temperature and Pressure
- Output power fixed at 40 kW, regardless of range
- Target range varies between 50 – 1000 meters
- Note that Fraunhofer Range $\frac{2D^2}{\lambda} \approx 2500$ meters

  (i.e. target range is well within the near-field (Fresnel) region)

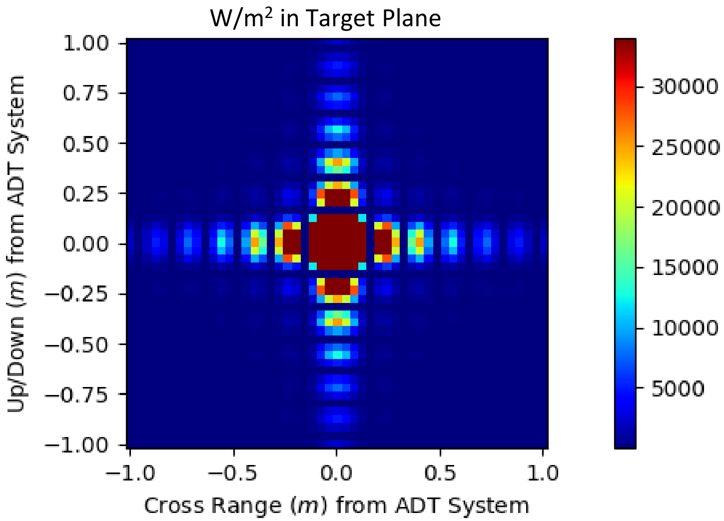
Comparing Modeling Approaches for Fixed Focus ADT Systems (2 of 5)

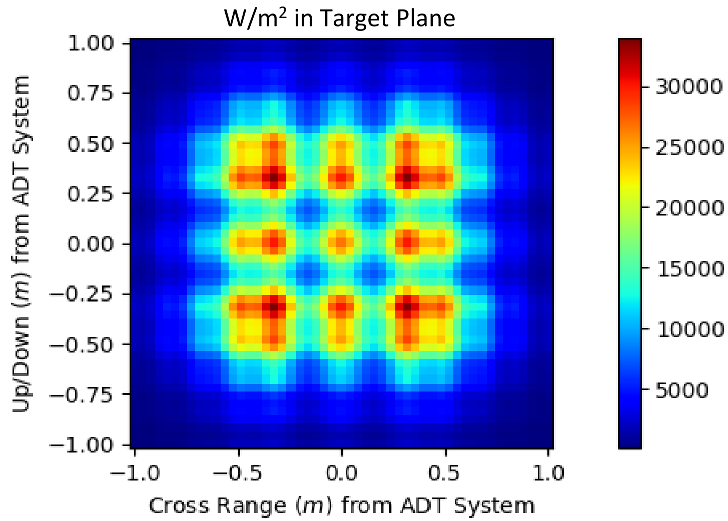
Range 100 m:

Far Field (FF) Approximation:

Near Field (NF) Extension:

Linear Scale:





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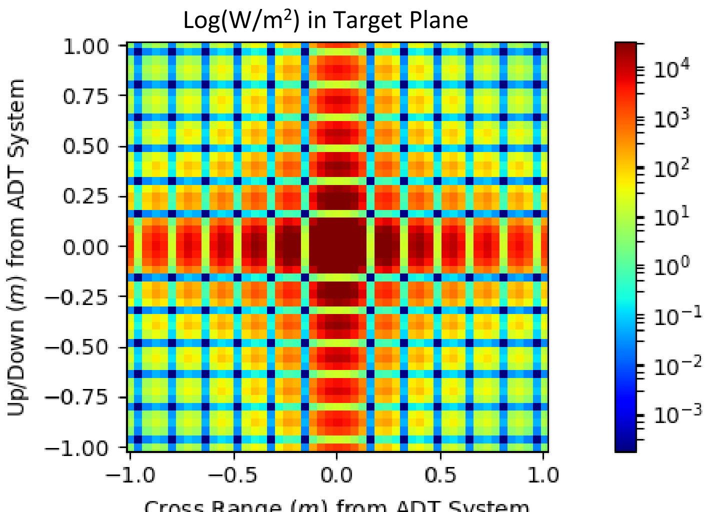

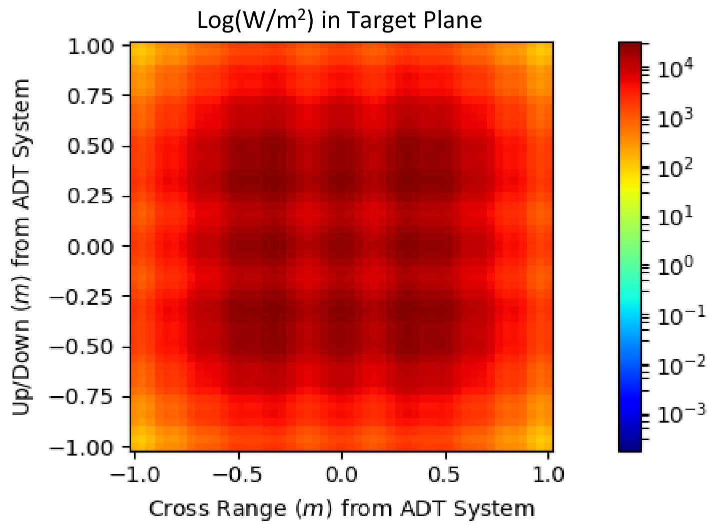

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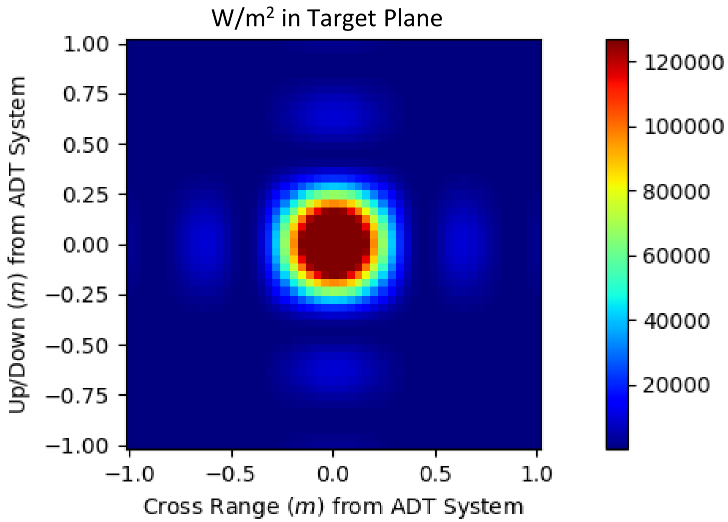
Comparing Modeling Approaches for Fixed Focus ADT Systems (3 of 5)

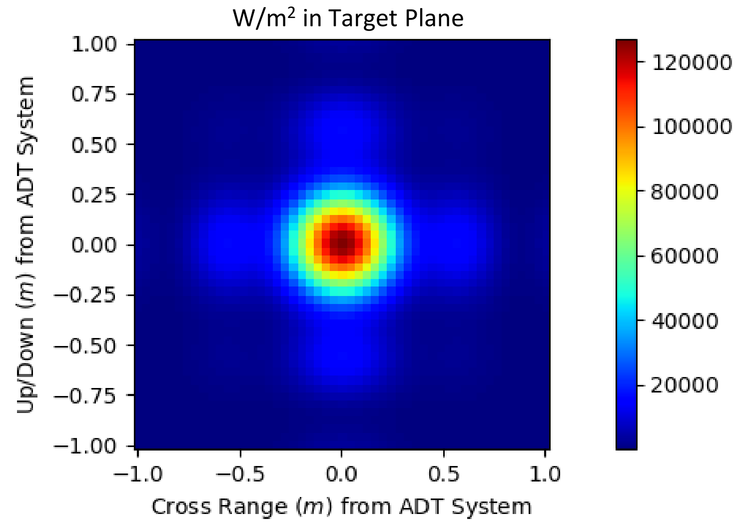
Range 275 m:

Far Field (FF) Approximation:

Near Field (NF) Extension:

Linear Scale:





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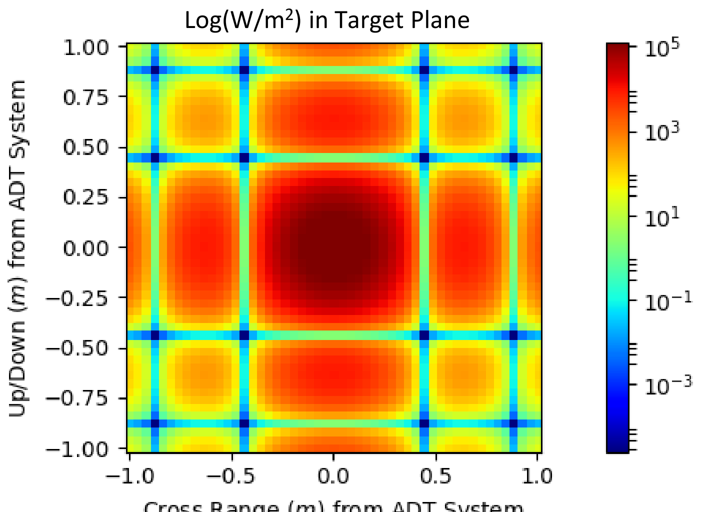
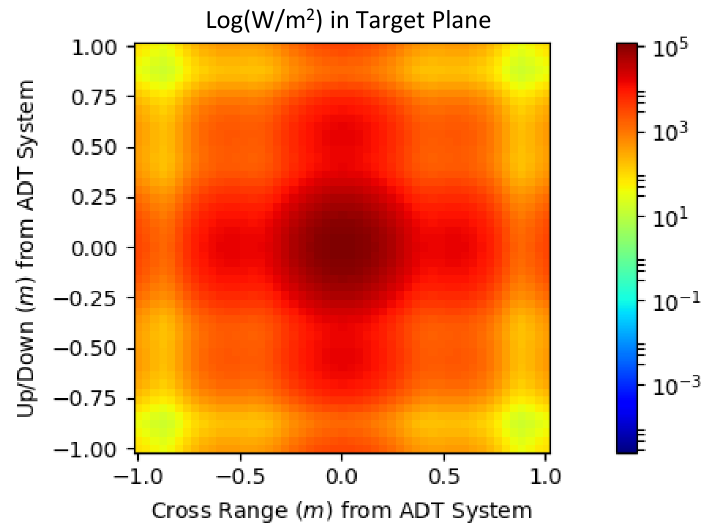


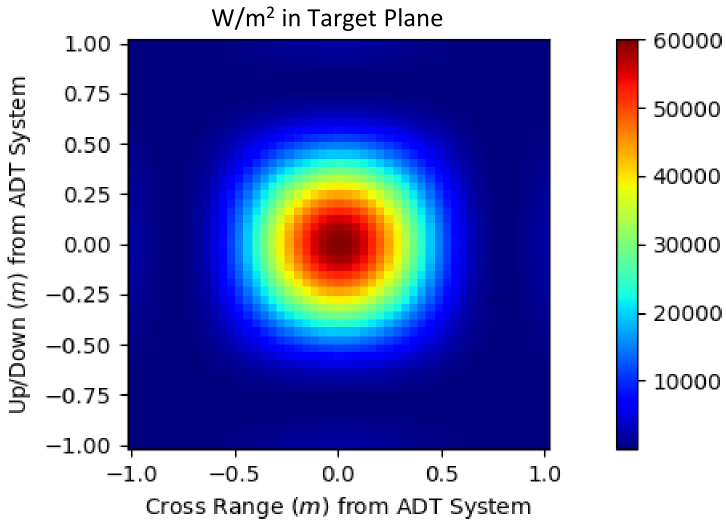


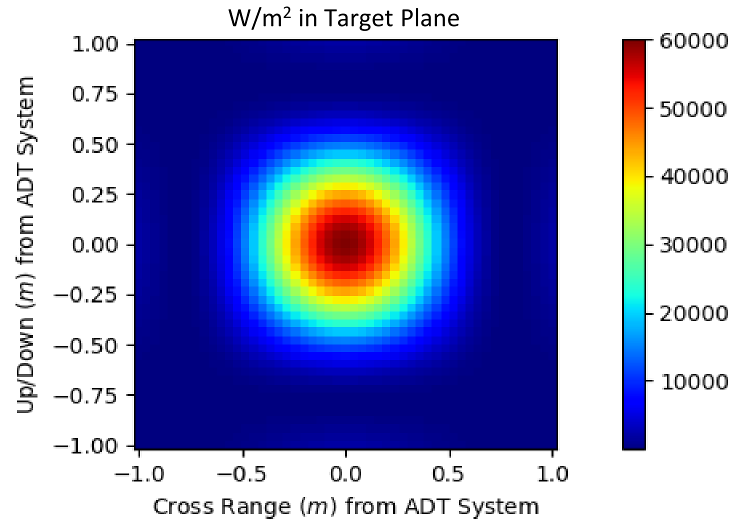
Comparing Modeling Approaches for Fixed Focus ADT Systems (4 of 5)

Range 500 m:

Far Field (FF) Approximation: | Near Field (NF) Extension:

Linear Scale:





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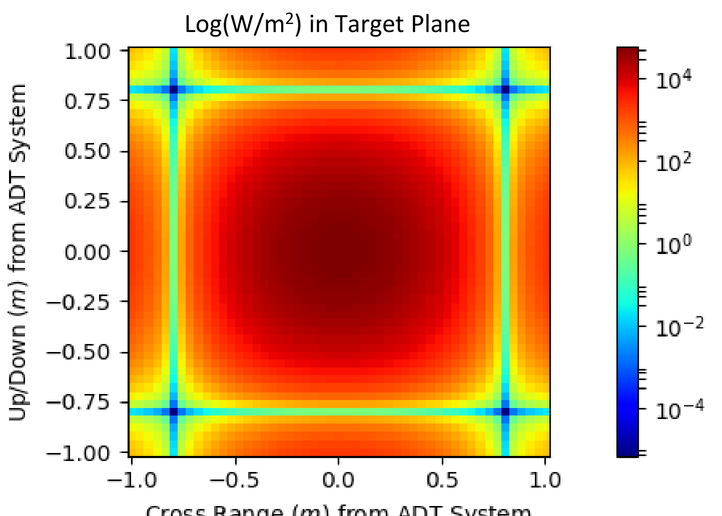
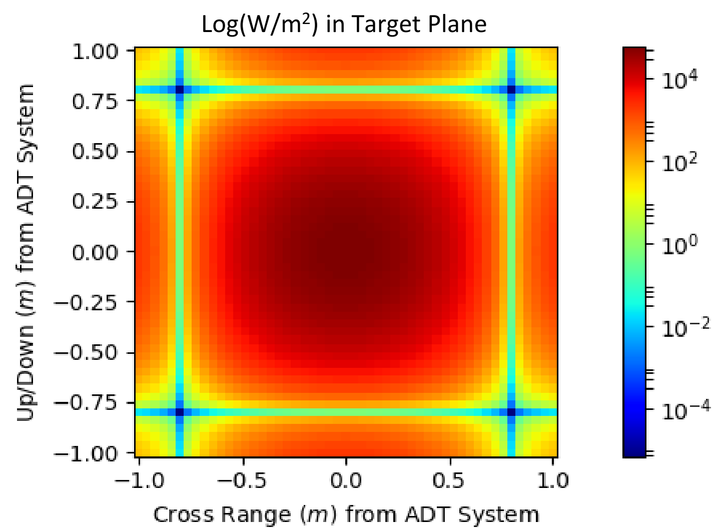
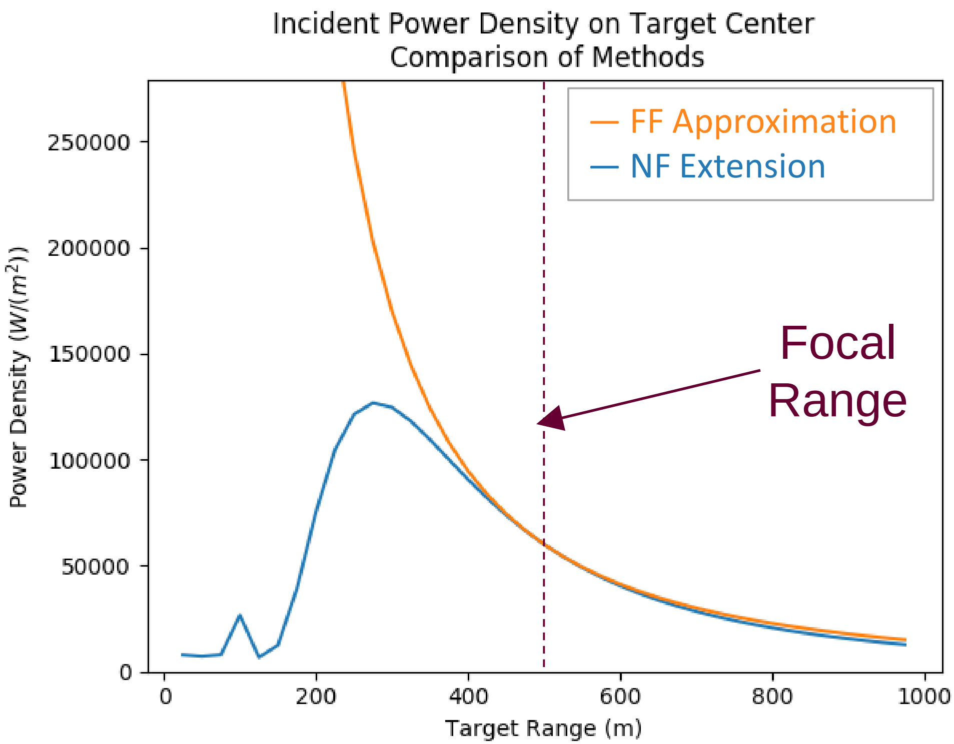




Comparing Modeling Approaches for Fixed Focus ADT Systems (5 of 5)



- NF & FF models produce different outputs for short target ranges

Comparing Modeling Approaches for Variable Focus ADT Systems (1 of 8)

Parameters used to model ***Variable Focus*** ADT System:

- Number of elements $32 \times 256 = 8192$ Total
- Spacing of elements $6.8 \times 0.8\ \lambda$
- Standard Temperature and Pressure
- Single Focus on Target
- Assume phase control on all elements for focusing
- Target range varies between 15 – 115 meters
- Note that Fraunhofer Range $\frac{2D^2}{\lambda} \approx 600$ meters

  (i.e. target range is well within the near-field (Fresnel) region)

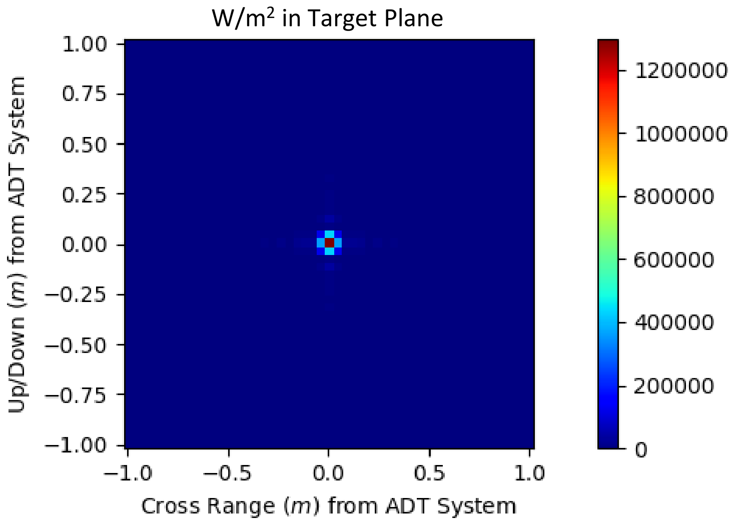
Comparing Modeling Approaches for Variable Focus ADT Systems (2 of 8)

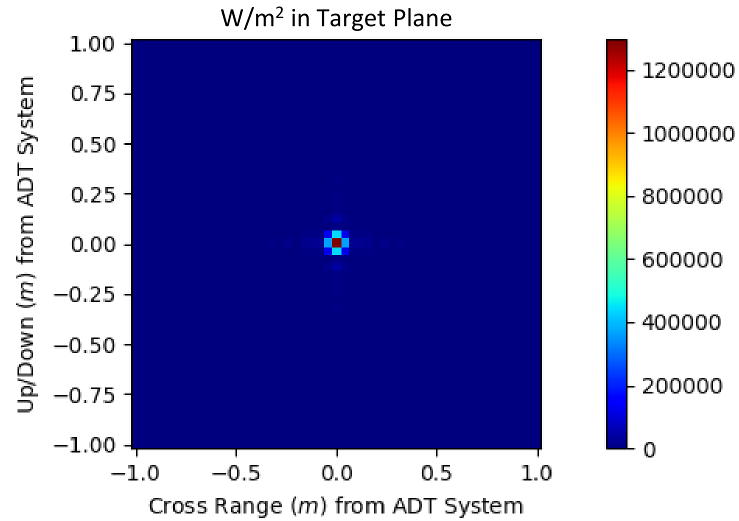
Range 15 m:

Far Field (FF) Approximation:

Near Field (NF) Extension:

Linear Scale:





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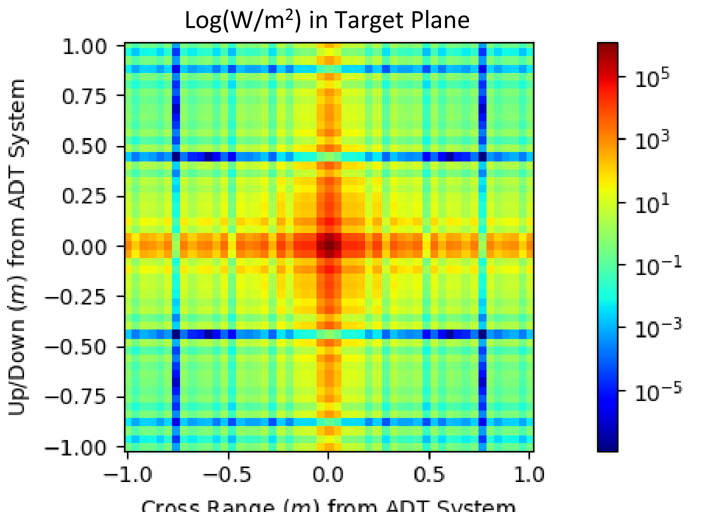

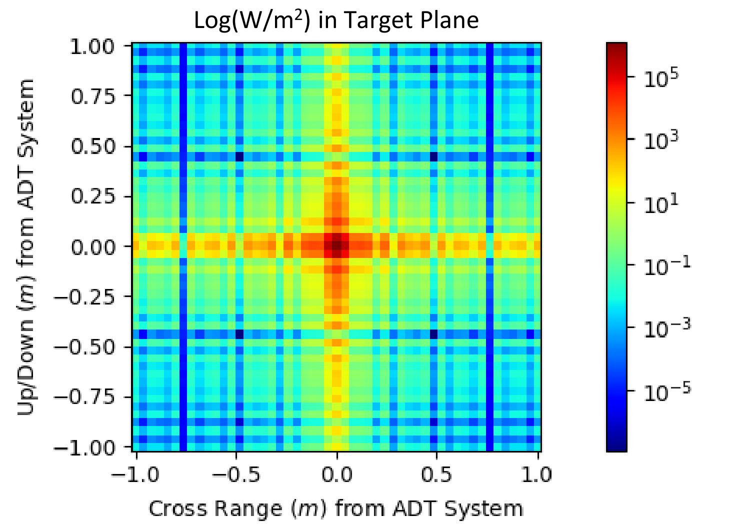

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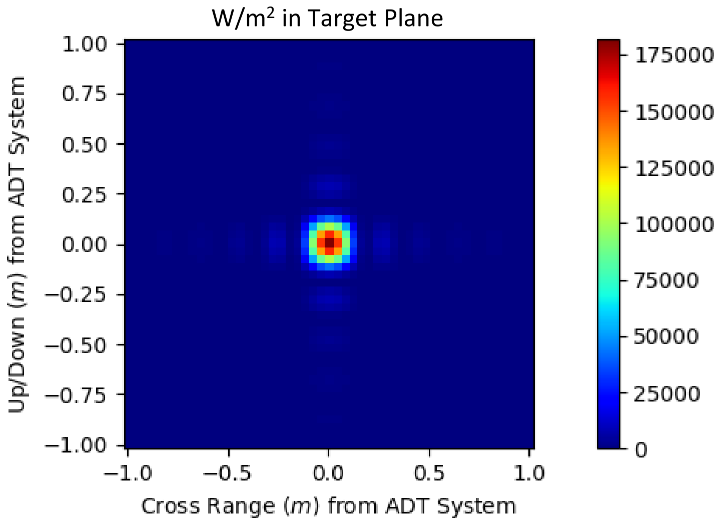
Comparing Modeling Approaches for Variable Focus ADT Systems (3 of 8)

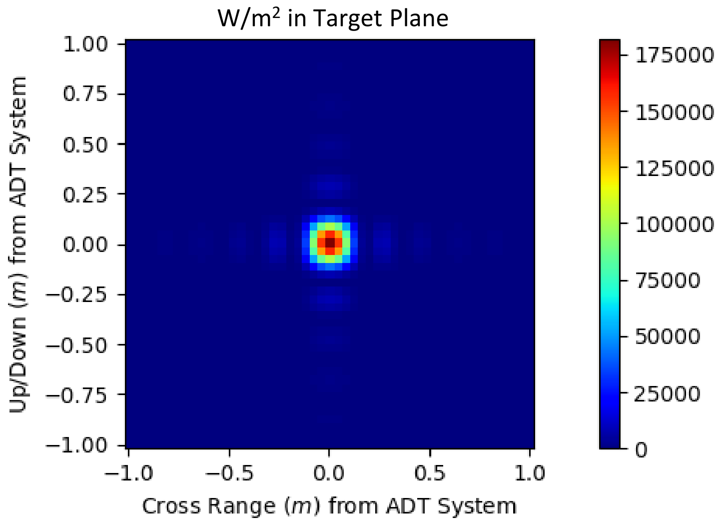
Range 40 m:

Far Field (FF) Approximation:

Near Field (NF) Extension:

Linear Scale:





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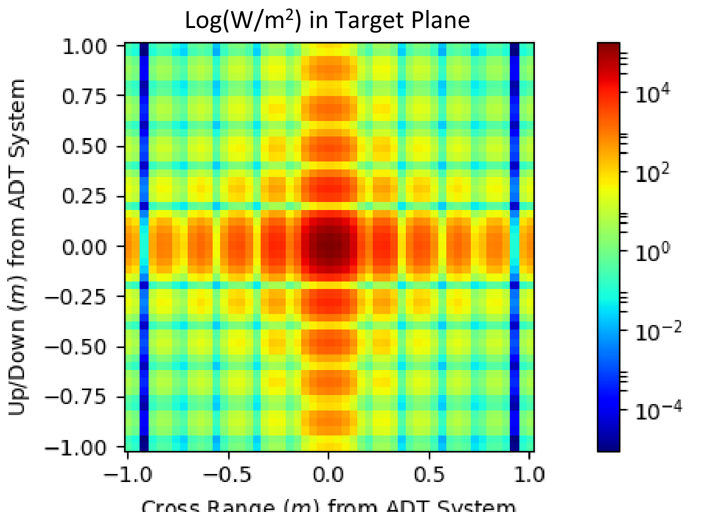
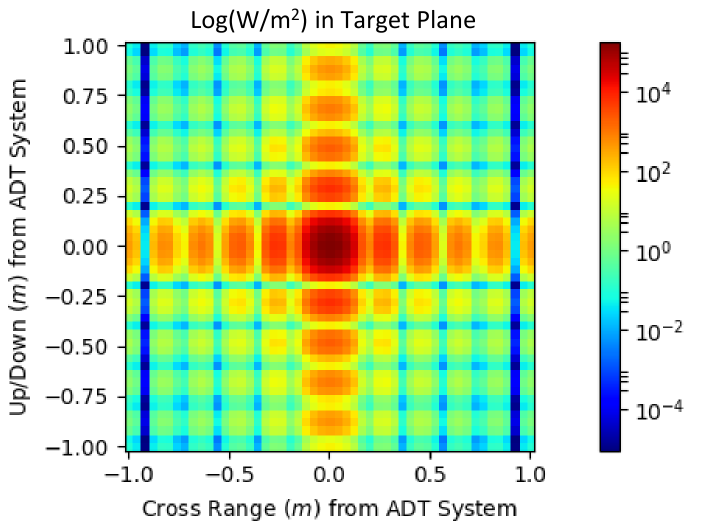




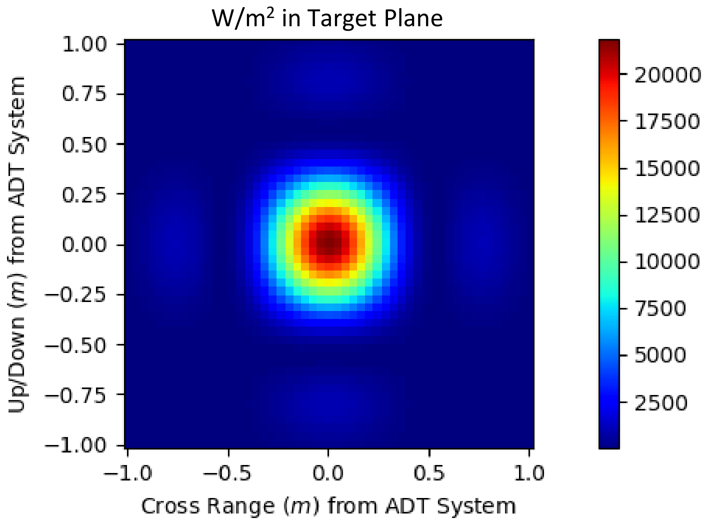
Comparing Modeling Approaches for Variable Focus ADT Systems (4 of 8)

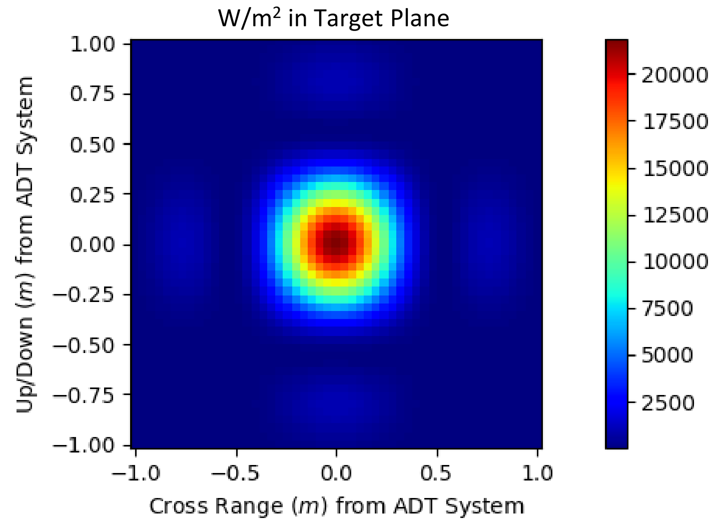
Range 115 m:

Far Field (FF) Approximation:

Near Field (NF) Extension:

Linear Scale:





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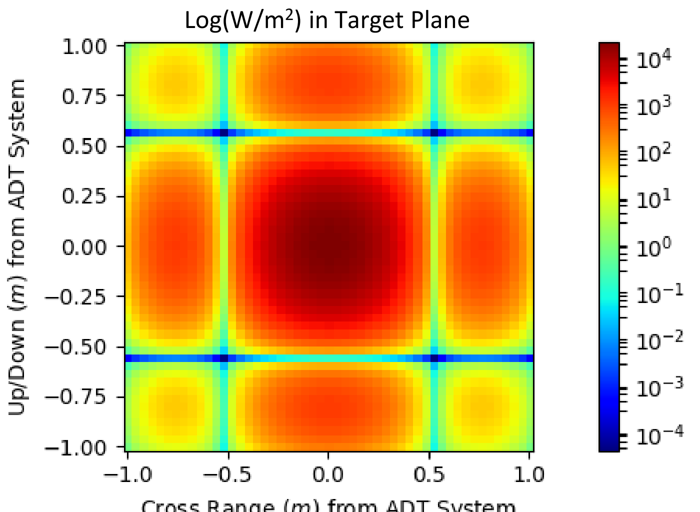

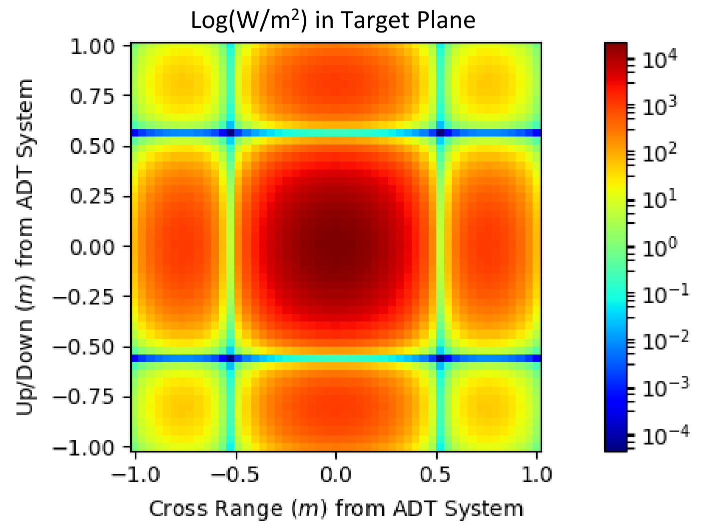

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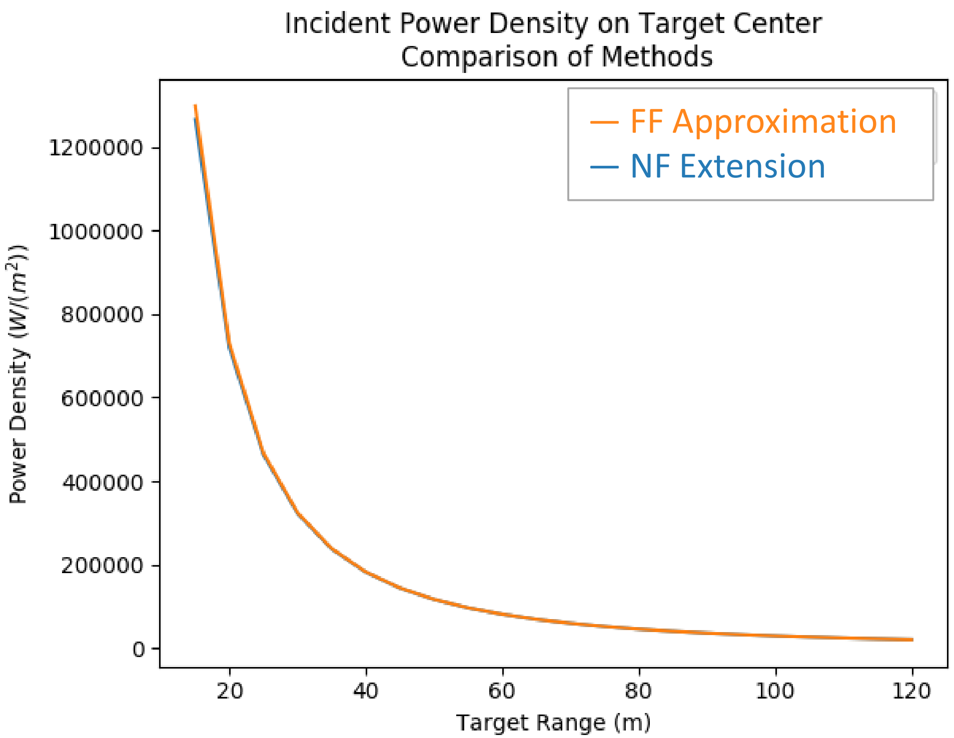
Comparing Modeling Approaches for Variable Focus ADT Systems (5 of 8)



- NF & FF models produce virtually identical outputs at target location
  - FF model has same fidelity as NF model
  - FF model is less computationally intensive than NF model
- Note that target is located at focal point where fields are purely diffractive
  - No surprise that FF model outputs good approximation in this region
  - However agreement between models is only seen near target location…

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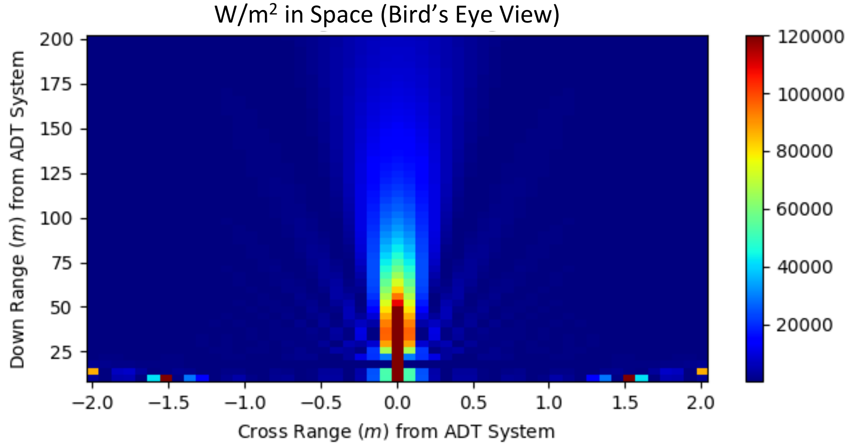
Comparing Modeling Approaches for Variable Focus ADT Systems (6 of 8)

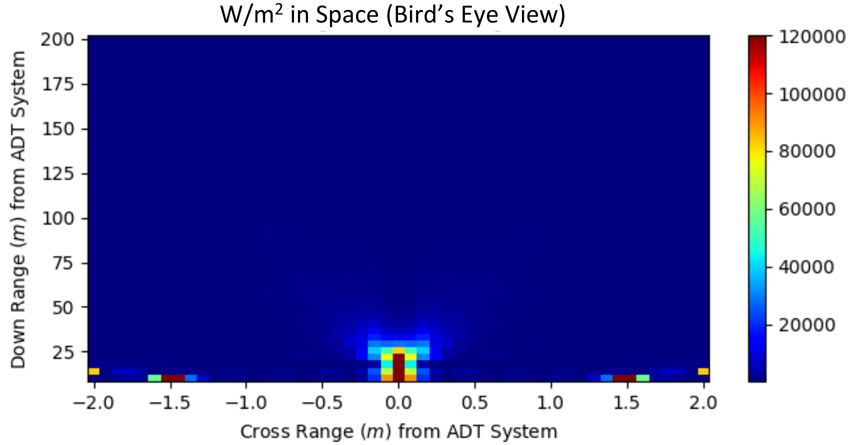
Range 15 m:

Far Field (FF) Approximation:

Near Field (NF) Extension:

Linear Scale:





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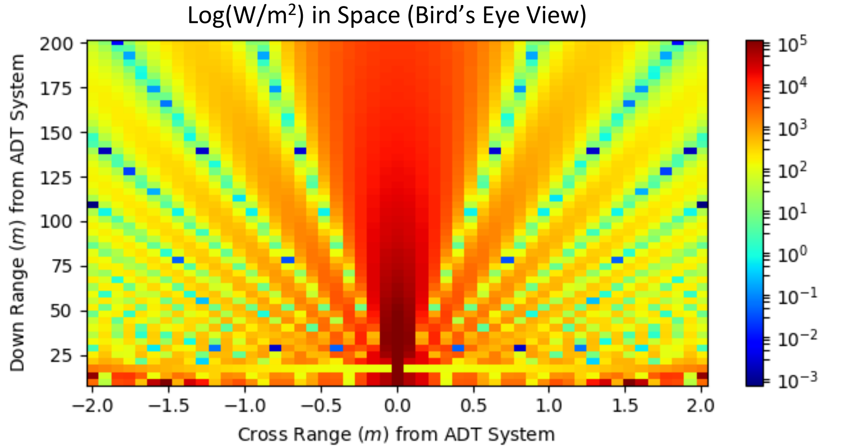
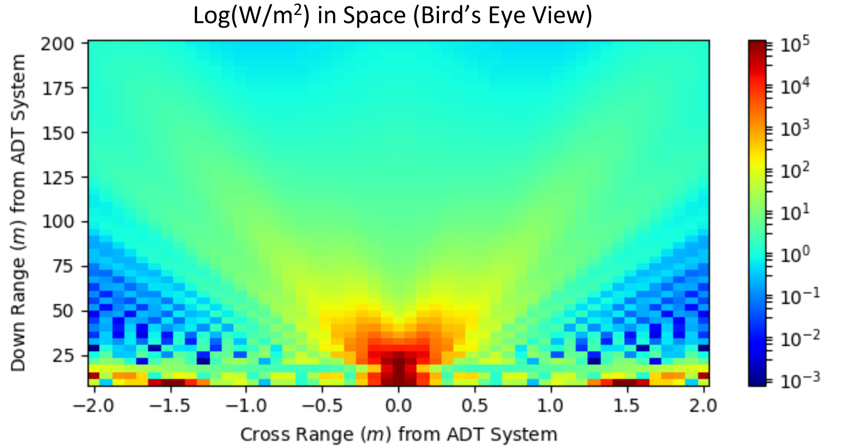


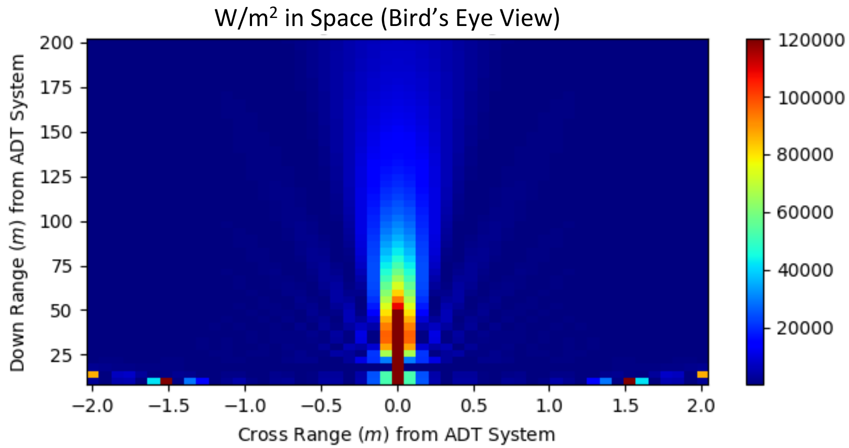


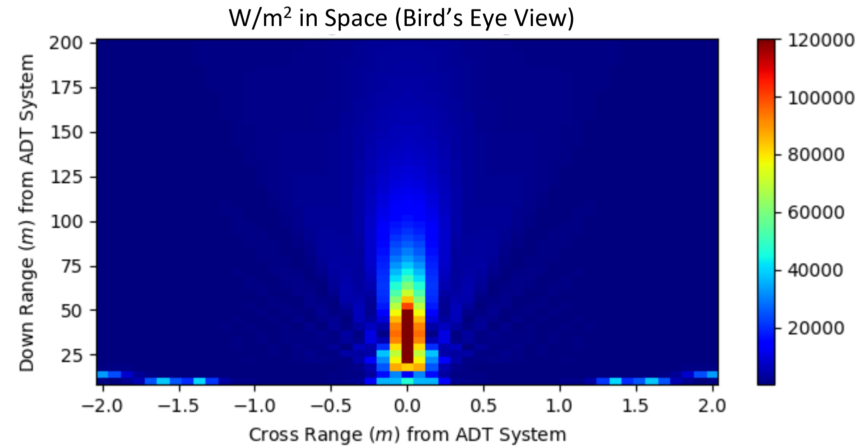
Comparing Modeling Approaches for Variable Focus ADT Systems (7 of 8)

Range 40 m:

Far Field (FF) Approximation: | Near Field (NF) Extension:

Linear Scale:





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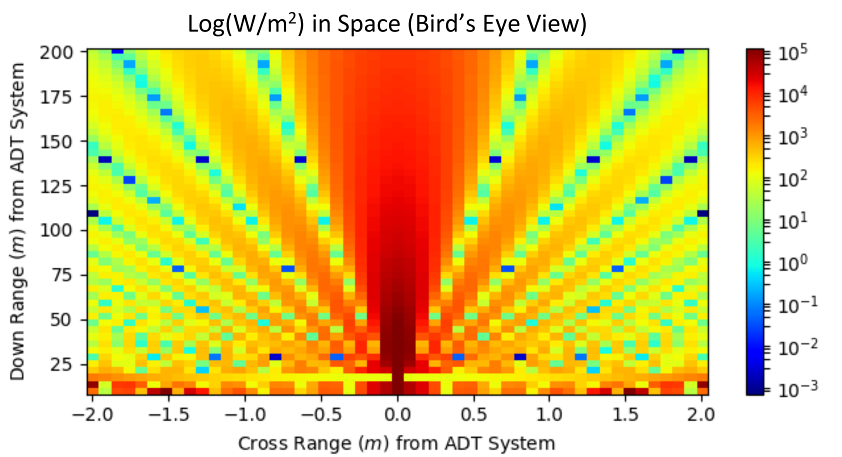
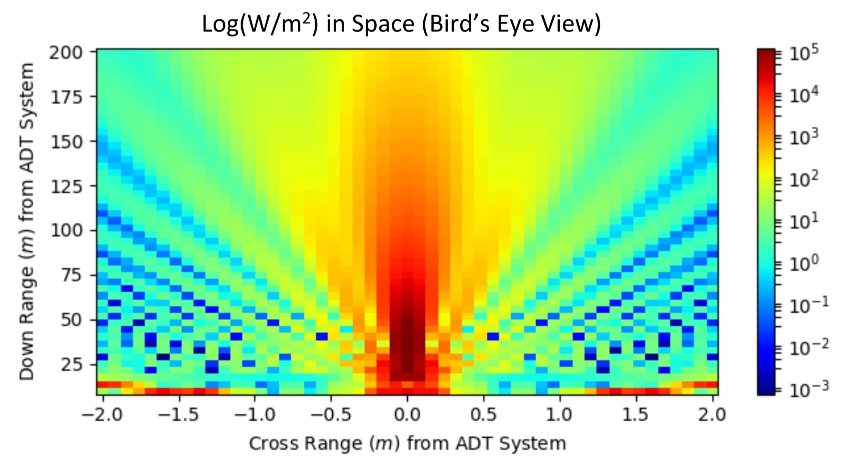




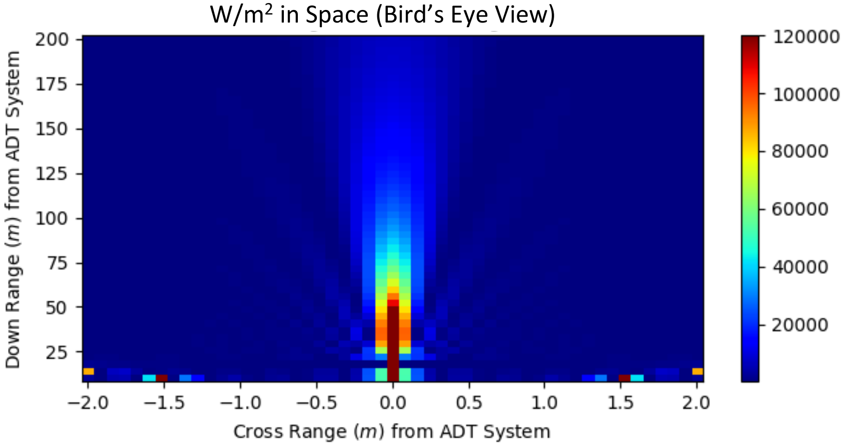
Comparing Modeling Approaches for Variable Focus ADT Systems (8 of 8)

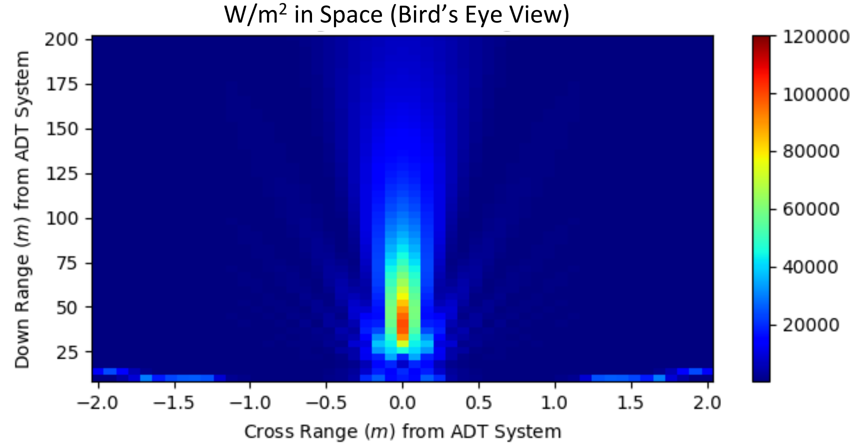
Range 115 m:

Far Field (FF) Approximation:

Near Field (NF) Extension:

Linear Scale:





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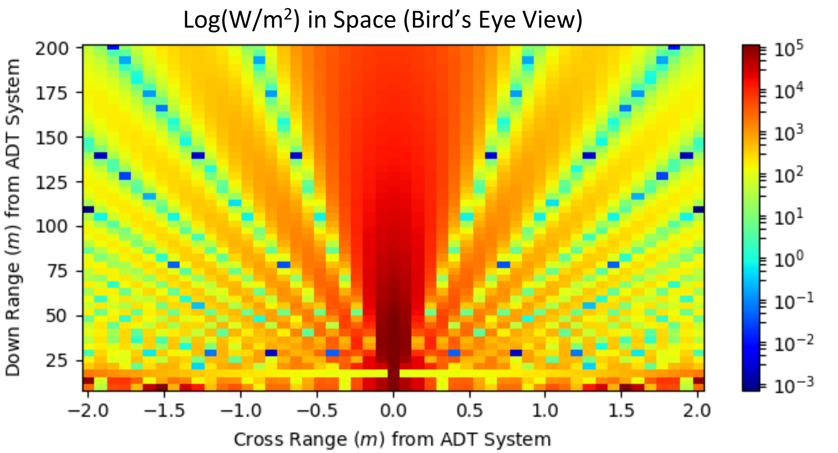

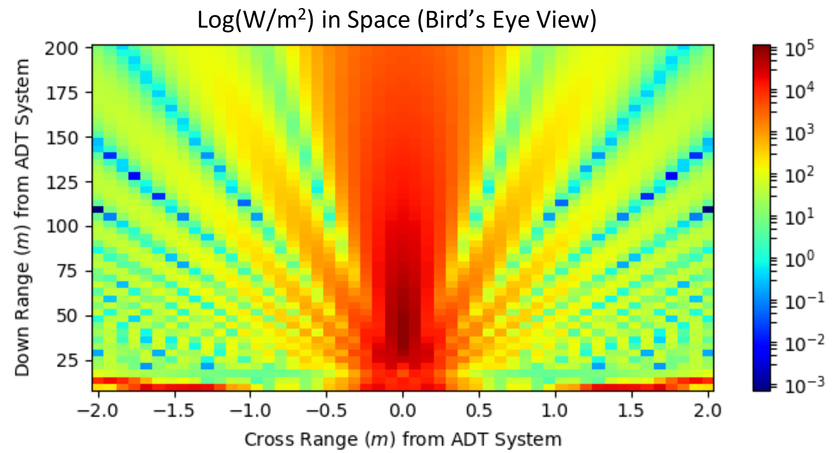

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Model Validation Study

- Compare NF & FF model outputs to field measurements of a ***variable focus*** ADT prototype
  - See: Parker et al. (2014) *Millimeter Wave Dosimetry Assessment of the SS-ADT*. AFRL
  - Validation against ***fixed focus*** ADT prototype will be performed in a future study
- Note: Models in this Validation Study differ from models in previous Comparison Study
  - Models in Comparison Study: Phase control performed on element-by-element basis, allowing for fine beam steering
  - Models in Validation Study: Elements' phase are controlled in blocks, providing more coarse beam steering

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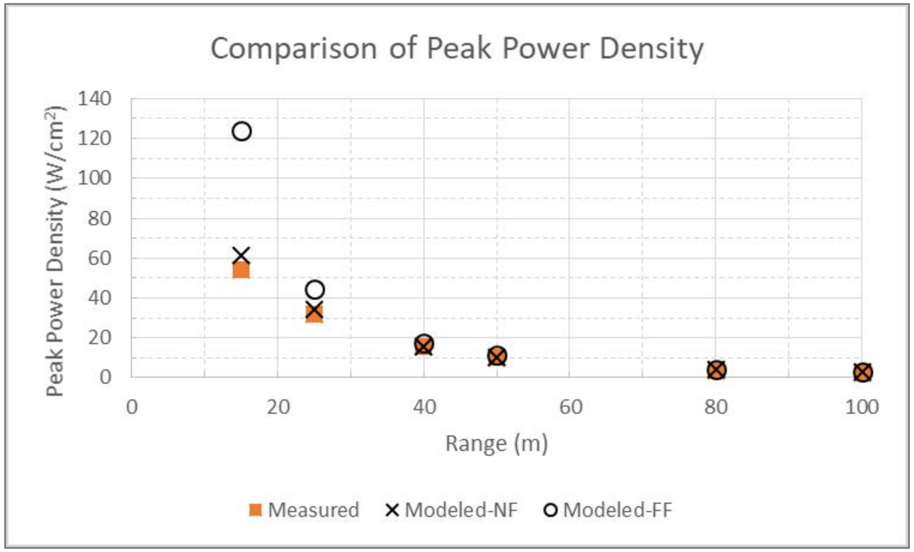
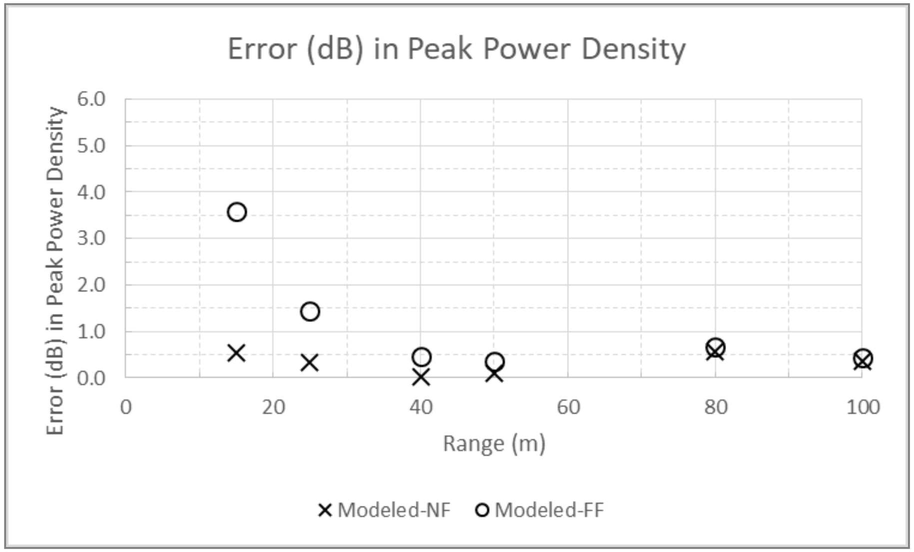
Model Validation Results





- NF model is in qualitative agreement (< 1 dB) with experimental measurements, even at short target ranges
  - Note: Measurement error not reported
- FF model differs considerably (> 1 dB) from experimental measurements at short target ranges
  - Likely due to coarse phase control

Conclusions

- Compared two simple propagation models for millimeter wave directed energy system
- Simple FF model may be adequate for investigations near focal point
  - FF & NF models produce similar estimates where diffractive fields are dominant – such as near the focal point (the target location for variable focused systems)
  - However, if system is not perfectly focused, then FF model fidelity depends on range of target and coarseness of phase control
- Validation results of NF model are encouraging
  - NF model is more computationally intensive than FF model, but still much simpler than full-wave solutions

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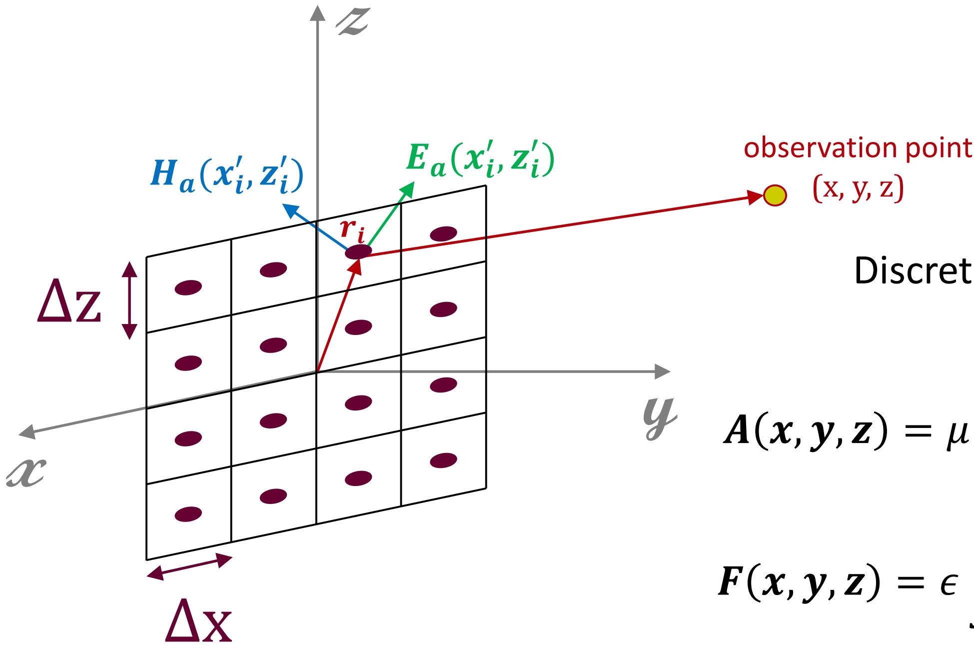
Backups

Field Equivalence Principle



Field Equivalence Principle:
Create fictitious currents from fields on aperture:

$$\boldsymbol{J_S} = \hat{\boldsymbol{y}} \times \boldsymbol{H_a}(\boldsymbol{x}, \boldsymbol{z})$$
$$\boldsymbol{M_S} = -\hat{\boldsymbol{y}} \times \boldsymbol{E_a}(\boldsymbol{x}, \boldsymbol{z})$$

Discretize aperture and take far field approximation to obtain vector potentials:

$$\boldsymbol{A}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = \mu \iint \boldsymbol{J_s}(x', y') \frac{e^{-jkr}}{4\pi r} dxdz \approx \mu \sum_{i=1}^{N} \frac{e^{-jkr_i}}{4\pi r_i} \boldsymbol{g_A}(x_i', z_i', \hat{\boldsymbol{r}})$$

$$\boldsymbol{F}(\boldsymbol{x}, \boldsymbol{y}, \boldsymbol{z}) = \epsilon \iint \boldsymbol{M_s}(x', y') \frac{e^{-jkr}}{4\pi r} dxdz \approx \epsilon \sum_{i=1}^{N} \frac{e^{-jkr_i}}{4\pi r_i} \boldsymbol{g_F}(x_i', z_i', \hat{\boldsymbol{r}})$$

Assuming uniform distribution for each element:

$$\boldsymbol{g_A}(x_i', z_i', \hat{\boldsymbol{r}}) = \boldsymbol{J_s}(x_i', z_i') \Delta x \Delta z \,\text{sinc}(k\, \hat{\boldsymbol{r}}_x \Delta x) \text{sinc}(k\, \hat{\boldsymbol{r}}_z \Delta z)$$
$$\boldsymbol{g_M}(x_i', z_i', \hat{\boldsymbol{r}}) = \boldsymbol{M_s}(x_i', z_i') \Delta x \Delta z \,\text{sinc}(k\, \hat{\boldsymbol{r}}_x \Delta x) \text{sinc}(k\, \hat{\boldsymbol{r}}_z \Delta z)$$

Radiated field:

$$\boldsymbol{E}(x, y, z) = -\boldsymbol{\nabla} \times \boldsymbol{F} + \frac{c^2}{j\omega} \boldsymbol{\nabla} \times \boldsymbol{\nabla} \times \boldsymbol{A}$$

Assuming uniform illumination on aperture and total output power, P:

$$|\boldsymbol{E_a}| = \sqrt{2\eta P/\text{area}}$$

Assuming Huygen's source:

$$\boldsymbol{H_a} = \frac{1}{\eta_0} \hat{\boldsymbol{n}} \times \boldsymbol{E_a}$$

If array is focused at $\boldsymbol{R_f}(x_f, y_f, z_f)$, the phase on aperture is assumed to be:

$$\boldsymbol{E_a}(x_i', z_i') = |\boldsymbol{E_a}| e^{j\,k\,|\boldsymbol{R_f} - \boldsymbol{r}_i'|}$$

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13. SUPPLEMENTARY NOTES

14. ABSTRACT

We consider low complexity beam propagation models of high powered, millimeter wave (95 GHz) systems. The goal is to achieve reasonable modeling fidelity with minimal compute power, allowing for rapid sampling in large parametric trade space studies. One model under consideration is the relatively simple Fraunhofer (e.g. “far field”) approximation which is commonly used in radar and high powered microwave systems. However at the frequency of interest, operational ranges for these systems can fall within the Fresnel zone where the assumptions of the Fraunhofer approximation are violated. As such we also construct a near field propagation model based on the field equivalence principle. This model is necessarily more complex than the Fraunhofer approximation, but is considerably less compute-intensive than full-wave solutions. We compare incident power estimates from the near field and Fraunhofer models for fixed focus and variable focus millimeter wave systems, showing that the models disagree primarily at ranges below the focal range as expected. Hence in this regime, we expect that the near field model to be the most appropriate. At the focal range and beyond, the models give similar results, suggesting that the Fraunhofer approximation may be sufficient for characterizing incident power near the focal point, even within the Fresnel zone.

15. SUBJECT TERMS

95 GHz; active denial technology (ADT); computational intensity; Field Equivalence Principle; Fraunhofer approximation; Millimeter Wave (MMW); Modeling and Simulation (M&S); simulation fidelity

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