Redefining possible

# R1400 (AKA GS1000-04) MPE



Defense › Environment › Intelligence

# MPE Ranges

- Worst Case scenario (scenario 1): Staring mode, boresight, 10% duty cycle, maximum output power
- R1400 Worst Case MPE ranges
  - Controlled:  ~9 meters
  - Uncontrolled:  ~ 22 meters

# RF Safety Exposure Definitions: FCC OET Bulletin 65

**Maximum permissible exposure (MPE).** The rms and peak electric and magnetic field strength, their squares, or the plane-wave equivalent power densities associated with these fields to which a person may be exposed without harmful effect and with an acceptable safety factor.

**Occupational/controlled exposure.** For FCC purposes, applies to human exposure to RF fields when persons are exposed as a consequence of their employment and in which those persons who are exposed have been made fully aware of the potential for exposure and can exercise control over their exposure. Occupational/controlled exposure limits also apply where exposure is of a transient nature as a result of incidental passage through a location where exposure levels may be above general population/uncontrolled limits (see definition above), as long as the exposed person has been made fully aware of the potential for exposure and can exercise control over his or her exposure by leaving the area or by some other appropriate means.

**General population/uncontrolled exposure.** For FCC purposes, applies to human exposure to RF fields when the general public is exposed or in which persons who are exposed as a consequence of their employment may not be made fully aware of the potential for exposure or cannot exercise control over their exposure. Therefore, members of the general public always fall under this category when exposure is not employment-related.

# OET Bulletin 65 Limits

**Table 1. LIMITS FOR MAXIMUM PERMISSIBLE EXPOSURE (MPE)**

**(A) Limits for Occupational/Controlled Exposure**

| Frequency Range (MHz) | Electric Field Strength (E) (V/m) | Magnetic Field Strength (H) (A/m) | Power Density (S) ($mW/cm^2$) | Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes) |
|---|---|---|---|---|
| 0.3-3.0 | 614 | 1.63 | (100)* | 6 |
| 3.0-30 | 1842/f | 4.89/f | $(900/f^2)$* | 6 |
| 30-300 | 61.4 | 0.163 | 1.0 | 6 |
| 300-1500 | -- | -- | f/300 | 6 |
| 1500-100,000 | -- | -- | 5 | 6 |

**(B) Limits for General Population/Uncontrolled Exposure**

| Frequency Range (MHz) | Electric Field Strength (E) (V/m) | Magnetic Field Strength (H) (A/m) | Power Density (S) ($mW/cm^2$) | Averaging Time $\|E\|^2$, $\|H\|^2$ or S (minutes) |
|---|---|---|---|---|
| 0.3-1.34 | 614 | 1.63 | (100)* | 30 |
| 1.34-30 | 824/f | 2.19/f | $(180/f^2)$* | 30 |
| 30-300 | 27.5 | 0.073 | 0.2 | 30 |
| 300-1500 | -- | -- | f/1500 | 30 |
| 1500-100,000 | -- | -- | 1.0 | 30 |

f = frequency in MHz *Plane-wave equivalent power density

# Other Standards MPE Limits

| | | Occupational (Controlled) [$mW/cm^2$] | General Public (Uncontrolled) [$mW/cm^2$] |
|---|---|---|---|
| **FCC** | *OET Bulletin 65* | 5 | 1 |
| **IEEE** | *IEEE Std C95.1* | 10 | 1 |
| **Canada** | *Safety Code 6* | 5 | 1 |
| **International** | *ICNIRP Guidelines* | 5 | 1 |

- Since FCC OET 65 is widely accepted and the minimum of all standards, these will be used for the analysis

# OET Bulletin 65 Equations

- OET Bulletin 65 has equations on pages 26-30 that apply to aperture antennas.
- These equations should provide coarse, conservative power estimates, even for a phase array.
- Simulation techniques (closed form expressions or WIPL) should provided better results in the antenna near field.
- The OET 65 equations and simulation should be equivalent in the far-field

# OET 65 Equation Summary (1)

**Antenna Surface.** The maximum power density directly in front of an antenna (e.g., at the antenna surface) can be approximated by the following equation:

$$S_{surface} = \frac{4P}{A} \qquad (11)$$

where: $S_{surface}$ = maximum power density at the antenna surface
$P$ = power fed to the antenna
$A$ = physical area of the aperture antenna

**Near-Field Region.** In the near-field, or Fresnel region, of the main beam, the power density can reach a maximum before it begins to decrease with distance. The extent of the near-field can be described by the following equation (**D** and **λ** in same units):

$$R_{nf} = \frac{D^2}{4\lambda} \qquad (12)$$

where: $R_{nf}$ = extent of near-field
$D$ = maximum dimension of antenna (diameter if circular)
$\lambda$ = wavelength

# OET 65 Equation Summary (2)

$$S_{nf} = \frac{16\eta P}{\pi D^2} \qquad (13)$$

where: $S_{nf}$ = maximum near-field power density
$\eta$ = aperture efficiency, typically 0.5-0.75
P = power fed to the antenna
D = antenna diameter

Aperture efficiency can be estimated, or a reasonable approximation for circular apertures can be obtained from the ratio of the effective aperture area to the physical area as follows:

$$\eta = \frac{\left(\frac{G\lambda^2}{4\pi}\right)}{\left(\frac{\pi D^2}{4}\right)} \qquad (14)$$

where: $\eta$ = aperture efficiency for circular apertures
G = power gain in the direction of interest relative to an isotropic radiator
$\lambda$ = wavelength
D = antenna diameter

If the antenna gain is not known, it can be calculated from the following equation using the actual or estimated value for aperture efficiency:

$$G = \frac{4\pi\eta A}{\lambda^2} \qquad (15)$$

where: $\eta$ = aperture efficiency
G = power gain in the direction of interest relative to an isotropic radiator
$\lambda$ = wavelength
A = physical area of the antenna

# OET 65 Equation Summary (3)

**Transition Region.** Power density in the transition region decreases inversely with distance from the antenna, while power density in the far-field (Fraunhofer region) of the antenna decreases inversely with the *square* of the distance. For purposes of evaluating RF exposure, the distance to the beginning of the far-field region (farthest extent of the transition region) can be approximated by the following equation:

$$R_{ff} = \frac{0.6\ D^2}{\lambda} \qquad (16)$$

where: $R_{ff}$ = distance to beginning of far-field
$D$ = antenna diameter
$\lambda$ = wavelength

The transition region will then be the region extending from $\mathbf{R_{nf}}$, calculated from Equation (12), to $\mathbf{R_{ff}}$. If the location of interest falls within this transition region, the on-axis

$$S_t = \frac{S_{nf}\ R_{nf}}{R} \qquad (17)$$

power density can be determined from the following equation:

where: $S_t$ = power density in the transition region
$S_{nf}$ = maximum power density for near-field calculated above
$R_{nf}$ = extent of near-field calculated above
$R$ = distance to point of interest

**Far-Field Region.** The power density in the far-field or Fraunhofer region of the antenna pattern decreases inversely as the square of the distance. The power density in the far-field region of the radiation pattern can be estimated by the general equation discussed earlier:

$$S_{ff} = \frac{PG}{4\pi R^2} \qquad (18)$$

where: $S_{ff}$ = power density (on axis)
$P$ = power fed to the antenna
$G$ = power gain of the antenna in the direction of interest relative to an isotropic radiator
$R$ = distance to the point of interest

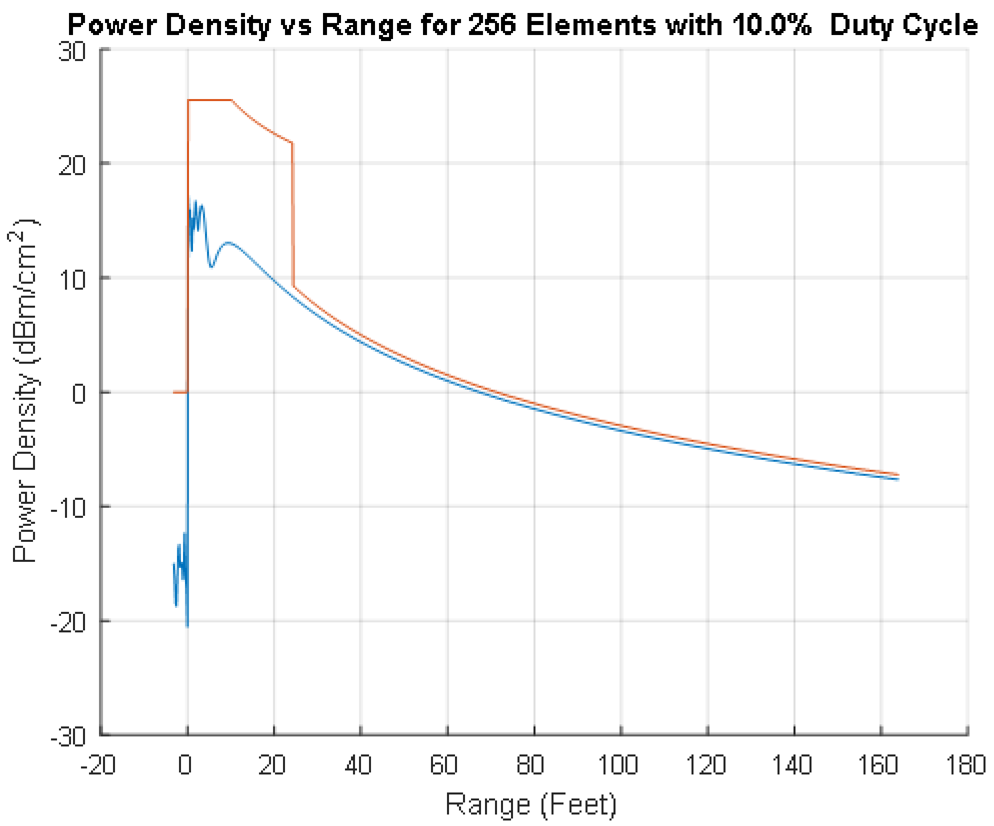
# Transmit Power Variables

- Several variables can affect the transmitted power
- The transmitted power from the OET65 equation 18 is an ***average*** power.
- Some, but not all, factors affecting the total output power:
  - Duty cycle of a pulsed signal
  - Scan rate of an antenna
  - Number of elements in an array
  - Antenna efficiency
  - Transmit amplifier peak power and post amplifier losses
  - Antenna pattern and desired location in that antenna pattern (ie. boresight)

# WIPL Simulation

- WIPL-D is an electromagnetic simulation tool that uses Method of Moments techniques to predict the performance of antenna structures
- The tool can be used to predict the power density of a phased array antenna at various ranges
- To get the proper power density, the output of WIPL-D must be scaled by the proper element power with respect to the generator voltages and impedances used in the model

# WIPL-D Results vs. OET65 Prediction




- Assumptions:
  - 4W peak amplifier power
  - 2dB loss post amplifier
  - 256 total elements (8x32 array)
  - Duty Cycle: 10%
  - Located at boresight of antenna

Red Line: OET 65 Equations

Blue Line: WIPL-D simulation

*Note: OET and sim are close in the far-field*

**Estimated MPE ranges:**

- **Uncontrolled: 19.2m**
- **Conctrolled: 9.1m**

# Power Density Closed Form Expression

- The power density at any observation point from the array face is approximated by (see Addendum and References for derivation):

$$P_T(r,\theta,\phi) = \frac{P_{rad,n} DF}{4\pi}\left|\sum_{i=1}^{N}\sqrt{\cos^{\alpha}\theta_i}\, e^{-jkr_i\cdot\hat{r}_0}\frac{a_i e^{-jkR_i}}{R_i}\right|^2 \qquad (1)$$

*This equation is valid for both near and far-field distances

Where

$P_{rad,n}$ = *Power Radiated Per Element*

$\theta_i$ = *Angle off boresight (relative to $i^{th}$ element, rad)*

$\alpha$ = *Element Pattern Exponent*

$N$ = *Total number of elements in array*

$k$ = *Free - space wavenumber ($m^{-1}$)*

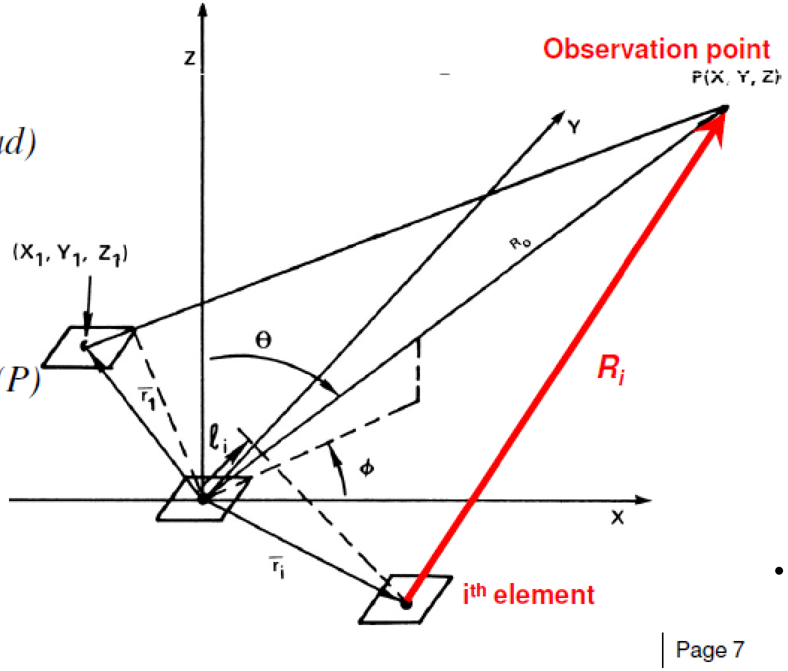
$R_n$ = *Range from $i^{th}$ element to observation point (P)*

$= \sqrt{(x_{obs}-x_i)^2 + (y_{obs}-y_i)^2 + (z_{obs}-z_i)^2}$

$r_i$ = *location of $i^{th}$ element ($x_i, y_i, z_i$)*

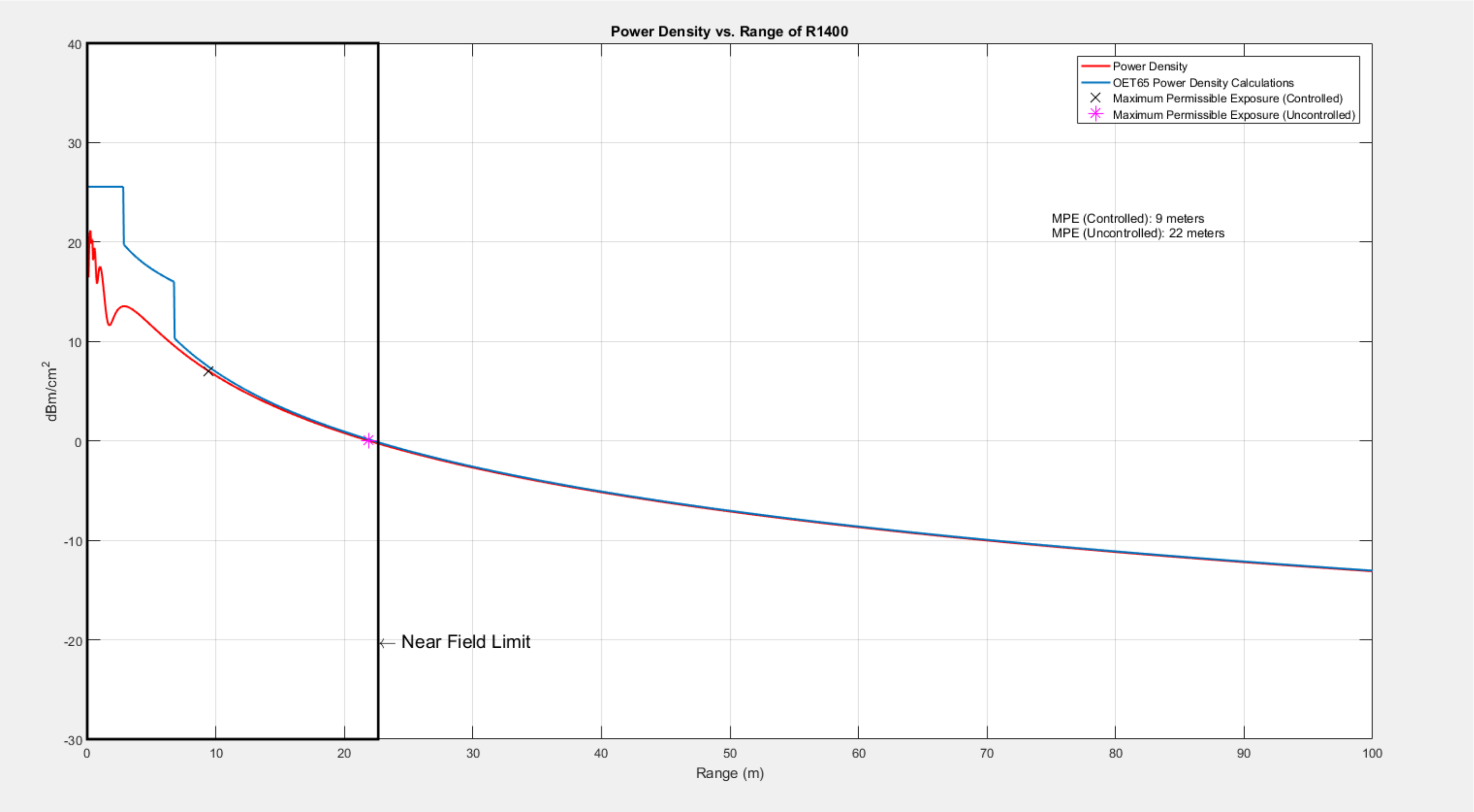
$\hat{r}_0$ = *pointing vector*

$= \hat{x}u_0 + \hat{y}v_0 + \hat{z}\cos\theta_0$ *(u,v are direction cosines)*



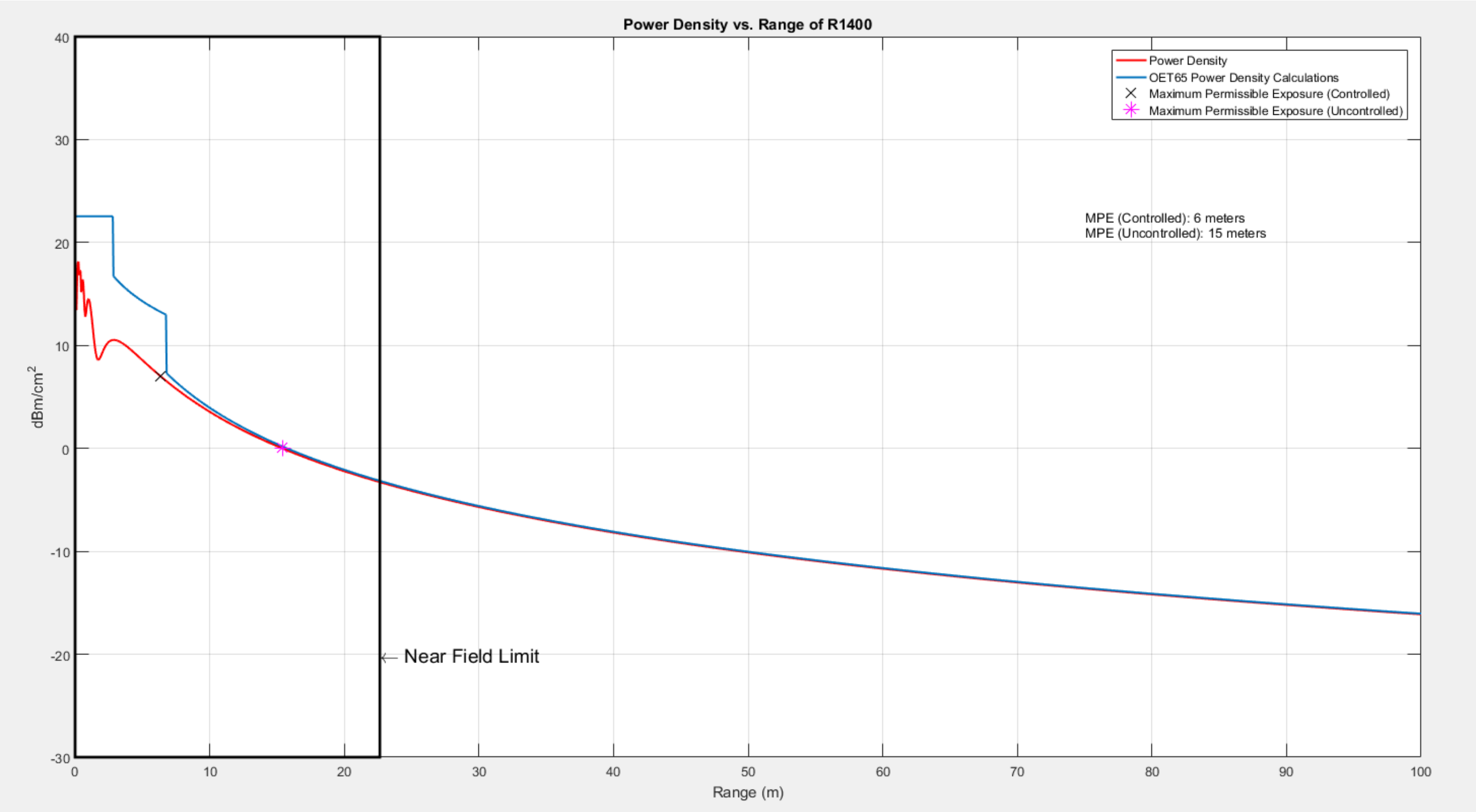

- Reference: "Analysis of Power Density Levels For Raytheon Prototype Radar Demonstration System (PRDS)"
- See Appendix for derivation of this with assumptions

# Closed Form Expression vs. OET65 Prediction:  Scenario 1




- Assumption:
  - 4W peak amplifier power
  - 2dB loss post amplifier
  - 256 total elements (8x32 array)
  - Duty Cycle: 10%
  - Boresight
    - Scanrate: 0Hz, staring mode
    - Element gain: 5.7dBi
    - Antenna efficiency: 100%
    - Raised cosine exponent: 1
    - Frequency: 9.8GHz
    - Element pattern: Raised Cosine
    - Az Beamwidth: λ/(Aperture Size)

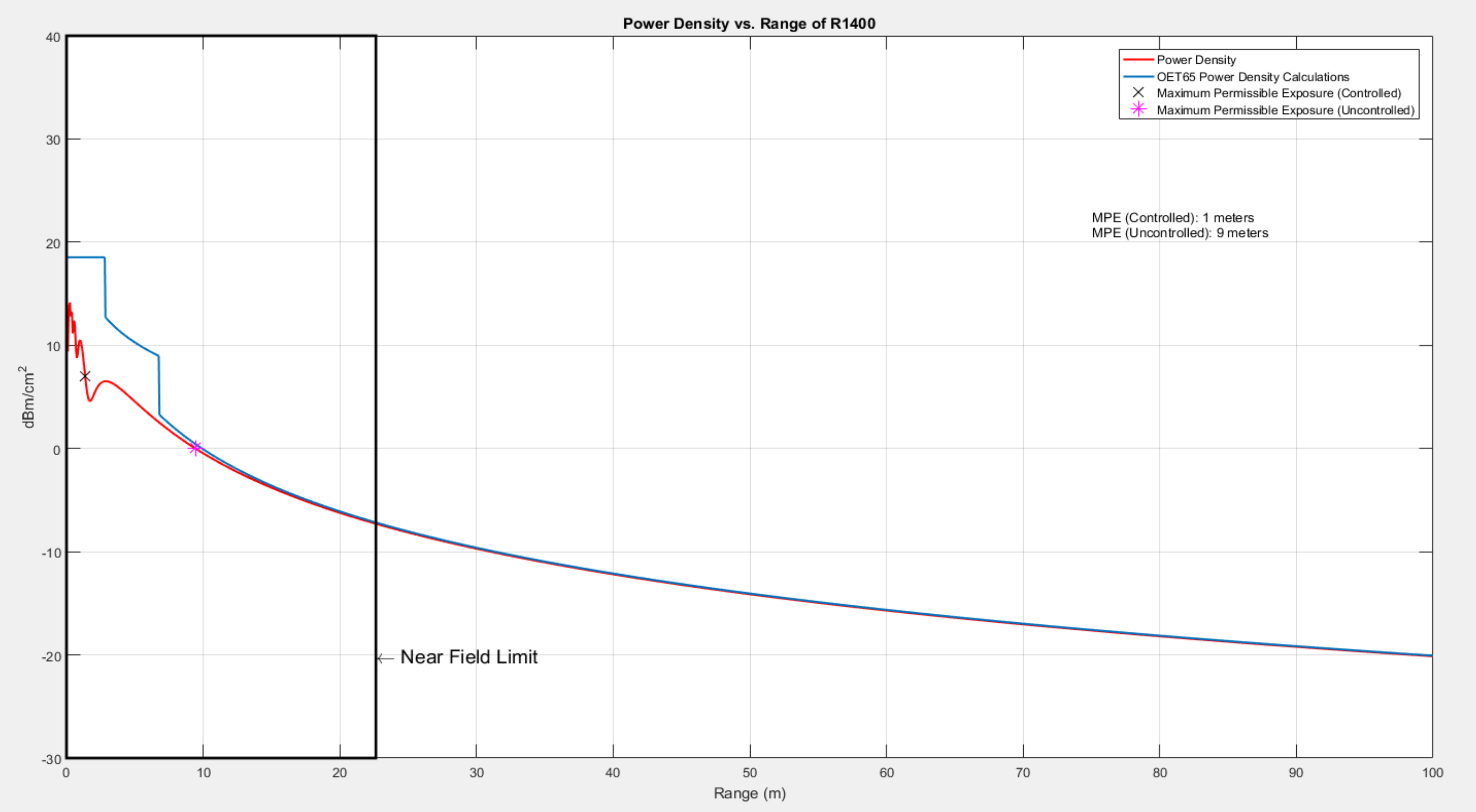
# Closed Form Expression vs. OET65 Prediction: Scenario 2




Assumption: Changes from Scenario 1 highlighted in red

- 4W peak amplifier power
- 2dB loss post amplifier
- 256 total elements (8x32 array)
- Duty Cycle: 5%
- Boresight
  - Scanrate: 0Hz, staring mode
  - Element gain: 5.7dBi
  - Antenna efficiency: 100%
  - Raised cosine exponent: 1
  - Frequency: 9.8GHz
  - Element pattern: Raised Cosine
  - Az Beamwidth: λ/(Aperture Size)

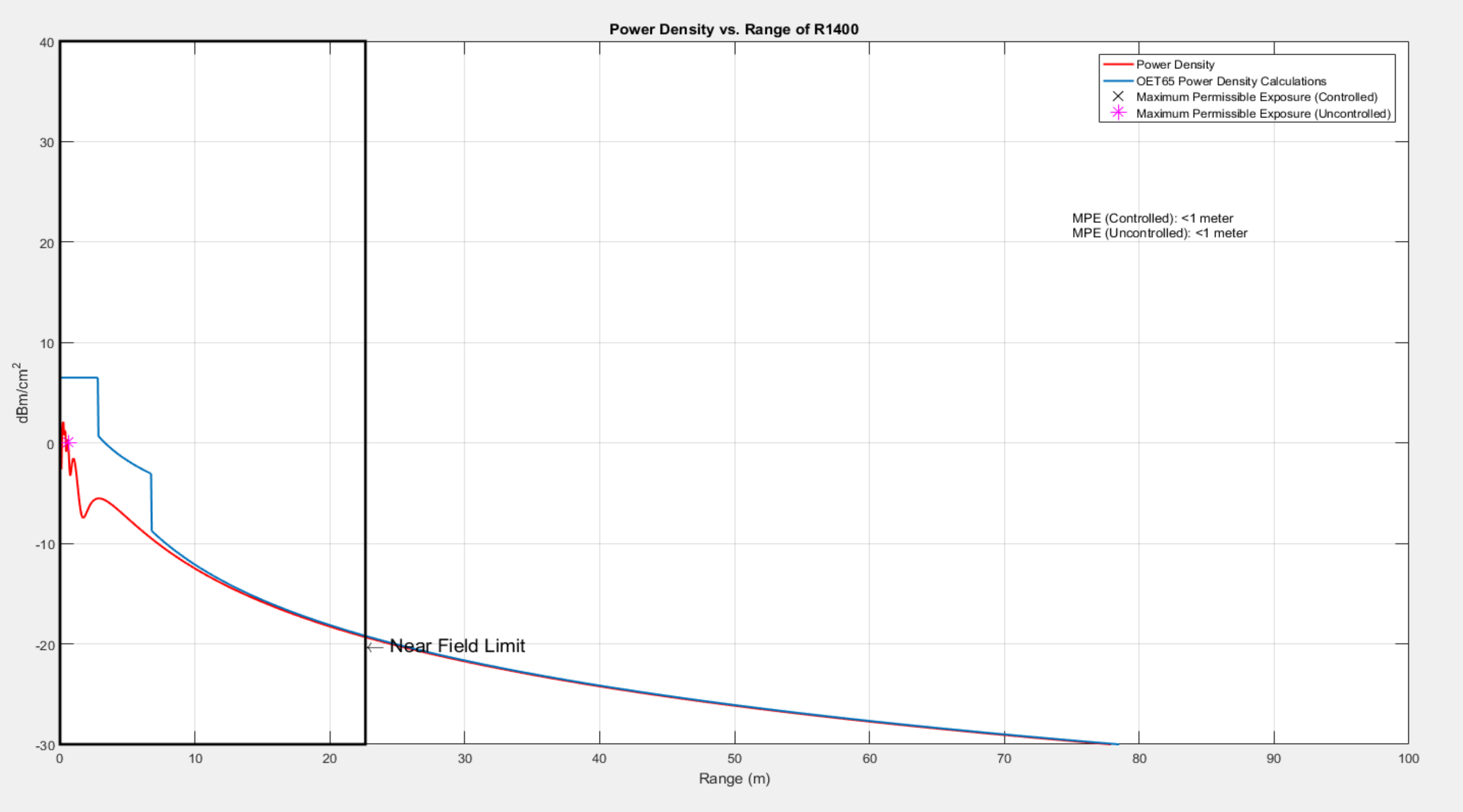
# Closed Form Expression vs. OET65 Prediction: Scenario 3




**Assumption:** Changes from Scenario 1 highlighted in red

- 4W peak amplifier power
- 2dB loss post amplifier
- 256 total elements (8x32 array)
- Duty Cycle: 5%
- Boresight
  - Scanrate: 0.25Hz, rotating mode
  - Element gain: 5.7dBi
  - Antenna efficiency: 100%
  - Raised cosine exponent: 1
  - Frequency: 9.8GHz
  - Element pattern: Raised Cosine
  - Az Beamwidth: λ/(Aperture Size)

# Closed Form Expression vs. OET65 Prediction:  Scenario 4




Assumption: Changes from Scenario 1 highlighted in red

- 4W peak amplifier power
- 2dB loss post amplifier
- 256 total elements (8x32 array)
- Duty Cycle: 5%
- Boresight

– Scanrate: 1Hz, rotating mode
– Element gain: 5.7dBi
– Antenna efficiency: 100%
– Raised cosine exponent: 1
– Frequency: 9.8GHz

– Element pattern: Raised Cosine
– Az Beamwidth: λ/(Aperture Size)

# Analysis Findings Summary

- OET65, WIPL-D, closed form expressions are very close in the far-field of an antenna
- Closed form expressions can be used in absence of MoM simulation with more assumptions
- WIPL-D is the best prediction of radiating near-field performance.