# The Potential for Ambient Plasma Wave Propulsion

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# Outline

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- A. Magnetosphere Modeling
  - Ex.: Jupiter
- B. Wave Propagation
  - Ray tracing
- C. Antenna System
  - Sizing and power loading

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# Justification

- Robust space exploration will ultimately require “living off the land”
- In-Situ propellants and propulsion will reduce launch needs
  - “Near Term” advanced propulsion (chemical, nuclear thermal, NEP) require IMLEO ~ 300 – 1000 mT
  - Feasibility of launching such masses on a regular basis is small
- Need to examine potential extraterrestrial sources for propulsion

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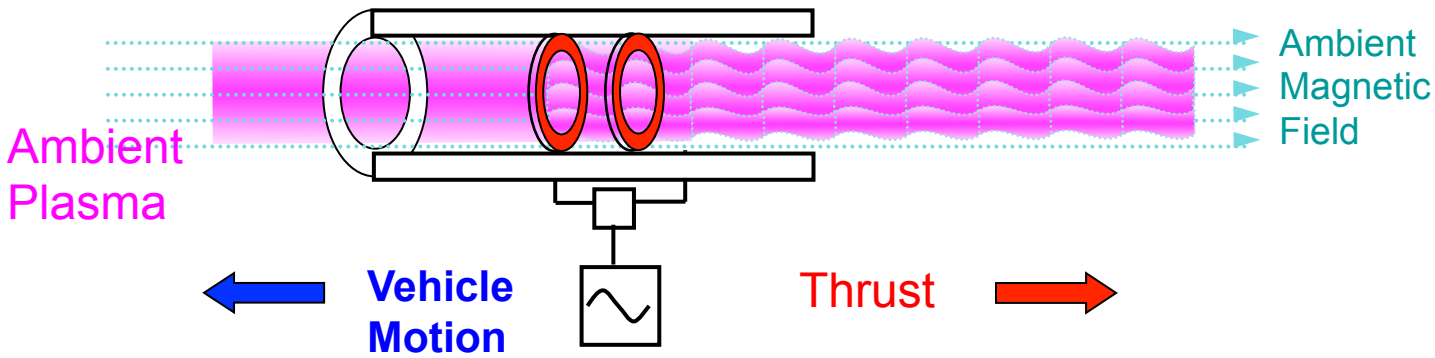
# Concept Description




- Utilize onboard power to couple to environment through plasma waves
  - First look: Alfven waves
    - Observed naturally in astrophysics
    - Postulated as mechanisms for heating and particle acceleration
- Radiate wave energy directionally to produce motion
  - Antennae designed to couple to correct wave and direction
  - Thrust ~ Wave field energy $\frac{\partial B^2}{2\mu_0}$

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# APPROACH

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# Analysis Approach

- Develop physical models for wave production/propulsion
- Assess possible environments
- Model wave propagation in relevant environments (Ray tracing)
- Use propagation results in system design (ANTENA rf plasma code)
  - Antenna size
  - Antenna loading (power)
  - Thrust

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# Alfven Wave Physics

- Low frequency waves in magnetized plasmas
- 3 modes:
  - Shear (|| B) $\omega = k\cos(\theta)V_A$
  - Compressional (isotropic) $\omega = k\,V_A$
  - Magnetoacoustic ($\perp$ B) $\omega^2 = k^2(v_A^2 + c_s^2)$
- Observed in terrestrial, Jovian, and Solar magnetospheres
  - Offered as possible explanation for coronal heating, acceleration of solar wind, Io plasma torus interactions

$$V_A = \sqrt{\frac{B_0^2}{\rho\,\mu_0}}$$

$$c_s = \sqrt{\frac{T_e}{M_i}}$$

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# Ray Tracing Approach

- Dispersion relation gives wavelength and frequency as functions of environment (B, ρ)

$$(\omega^2 - k_z^2 V_A^2)(\omega^4 - \omega^2 k^2 (V_A^2 + c_s^2) + c_s^2 V_A^2 k^2 k_z^2) = 0$$

$$\vec{V}_A(x.y,z) = \frac{\vec{B}(x.y,z)}{\mu_0 \rho(x,y,z)} \qquad c_s = \sqrt{\frac{kT_e}{M_i}} \qquad k = \sqrt{k_z^2 + k_\perp^2}$$

- Wavelength (k) depends on position through magnet and density fields
- Ray tracing follows wave energy as it propagates in magnetosphere
- Requires representative initial conditions
  - (x,y,z), (kx, ky, kz)

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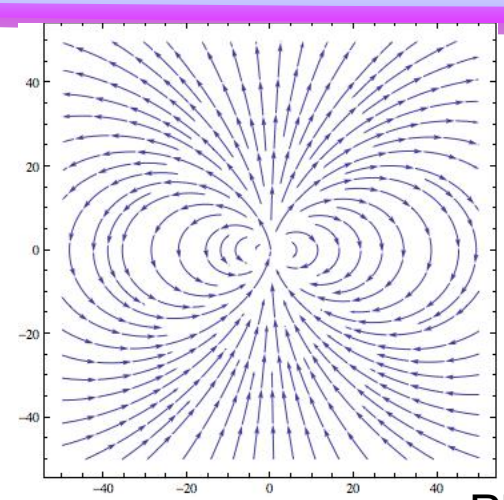
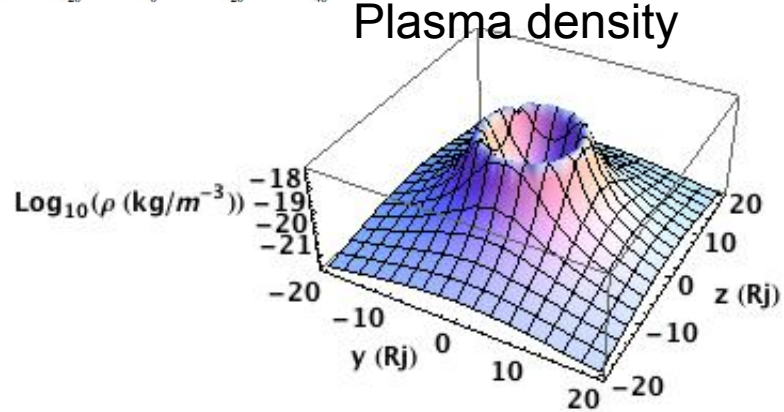
# Establish Potential Environments

- First approximation Magnetospheres
  - Dipole magnetic field
  - Axisymmetric density
  - Uniform $T_e$
- Calculate simplified local k for ray tracing
- Assess ray propagation in spatially varying fields




Magnetic Field

Plasma density

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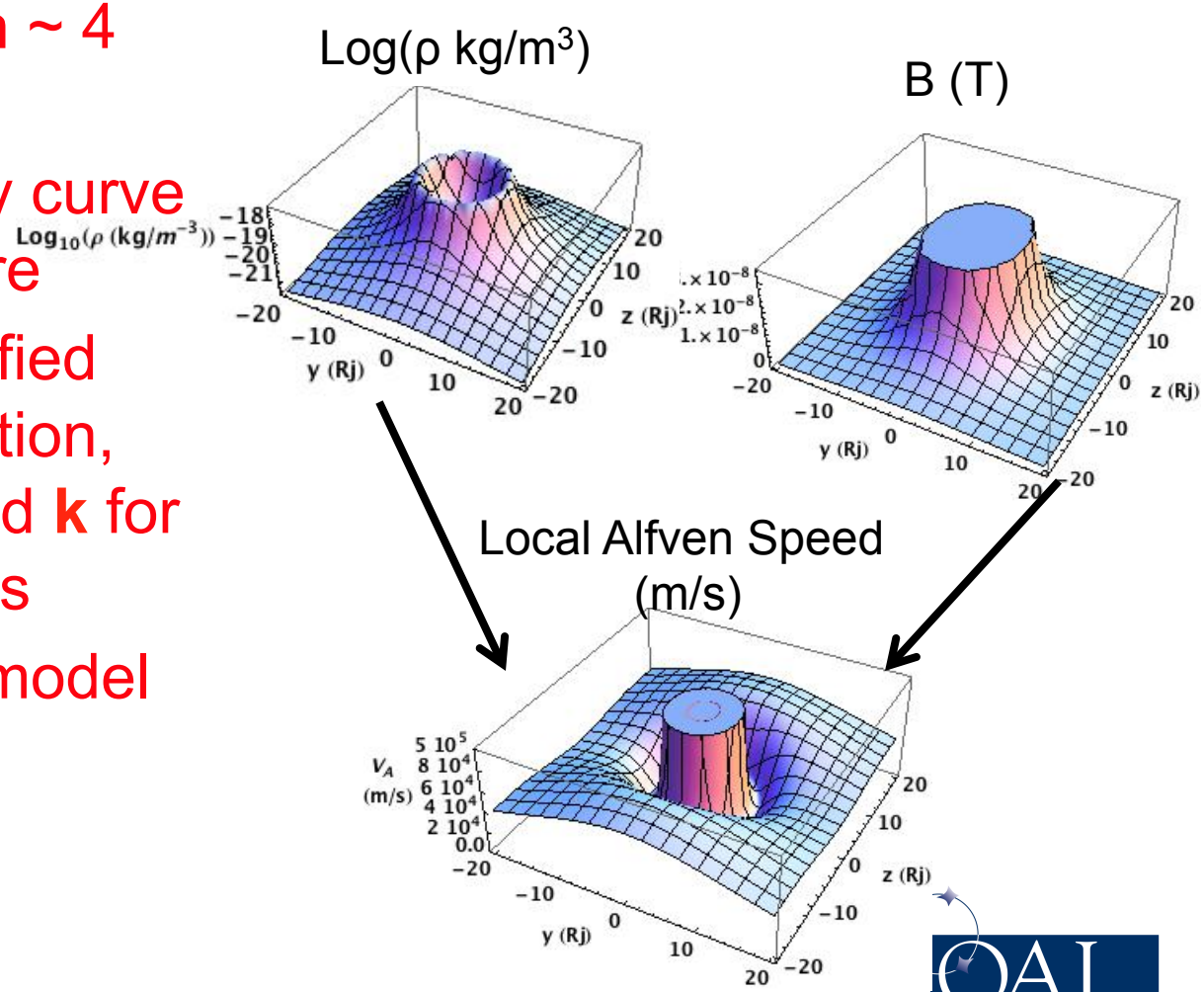
# Jovian Magnetosphere

- Dipole strength ~ 4 nG $Rj^3$
- Plasma density curve fit from literature
- Using a simplified dispersion relation, calculate ω, and **k** for initial conditions
- Use full fields model for ray tracing

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# Antenna Modeling

- Antennas determine the dominant axial and perpendicular wavelengths launched
  - Antenna design determines types of fields
    - E, B - Axial, radial, azimuthal
  - Antenna dimensions determine dominant wavelengths
- The desired wavelengths are determined from local B and density values

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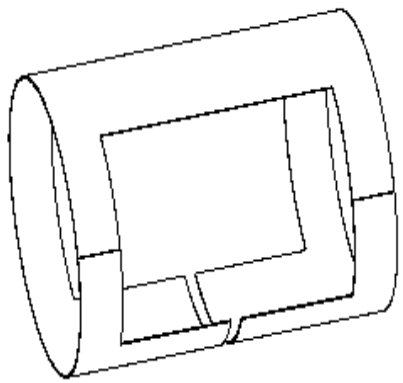
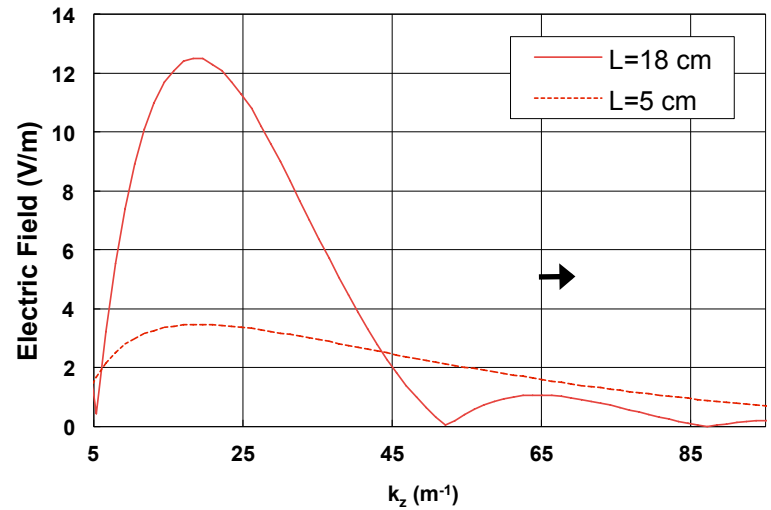
# ANTENA Code

- Warm plasma cylindrical wave code
- Originally designed for fusion wave heating applications
  - Radial profiles of $n_e$, $T_e$ (not self consistent)
  - Axially uniform $B_0$, $n_e$
  - Uses real antenna designs/wavelength spectra
  - Calculates radiated power, antenna/plasma coupling
- Can apply ANTENA to the calculated local plasma parameters to determine best antenna size, design for the wave propulsion application

# Example Antenna - Nagoya III






- Originally designed for ICRH heating in tokamaks
- Launches symmetric, left hand and right handed waves (m= 0,-1, 1)
- Antenna Length L gives peak coupling at wavelengths λ ~ 2L

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# RESULTS

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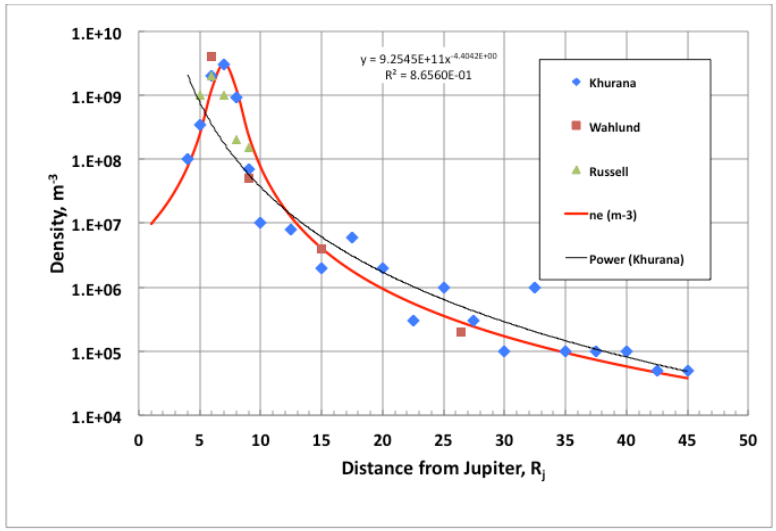
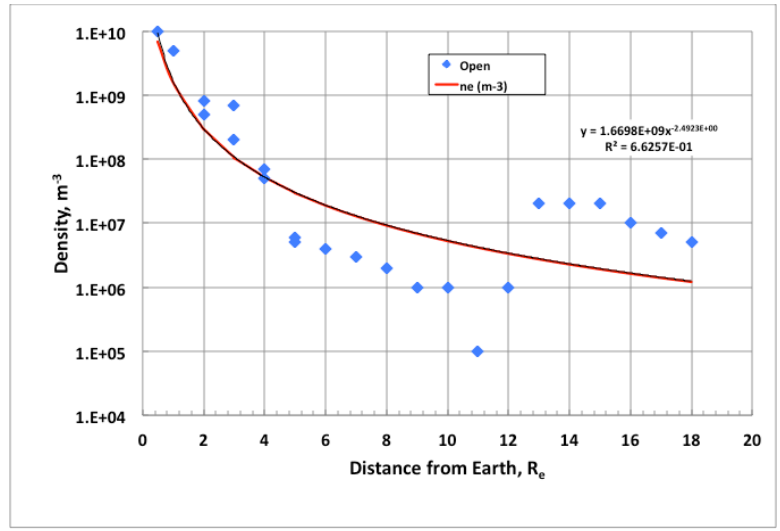
# Magnetosphere Models




- Standardized simplified model for dipole fields allows calculation structure to be applied to multiple environments
  - Jovian and Terrestrial environments described to date

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# Ray Tracing Analysis

- Ray tracing analysis generated from first principles in Mathematica
- Initial conditions generated for multiple Alfven modes throughout Jovian magnetosphere
  - Fast modes also depend on $k_\perp$ - assumed to be $\approx k_z$ for initial calculations
- Wave propagation has been examined throughout the Jupiter magnetosphere
  - Parallel and perpendicular waves observed
  - Currently examining results for resonance absorption and reflections

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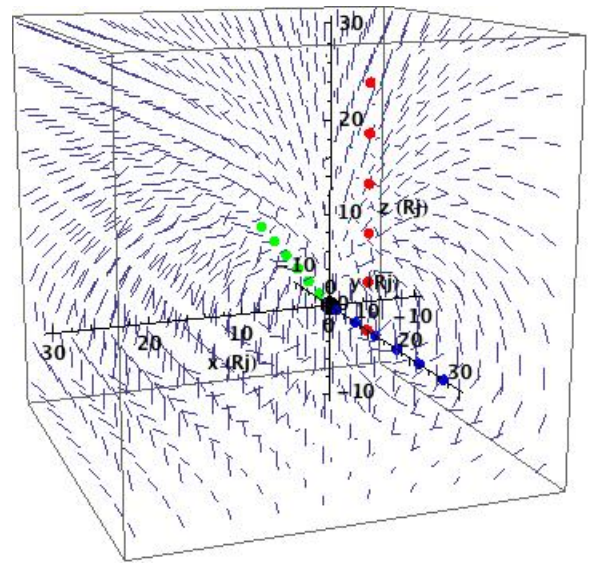
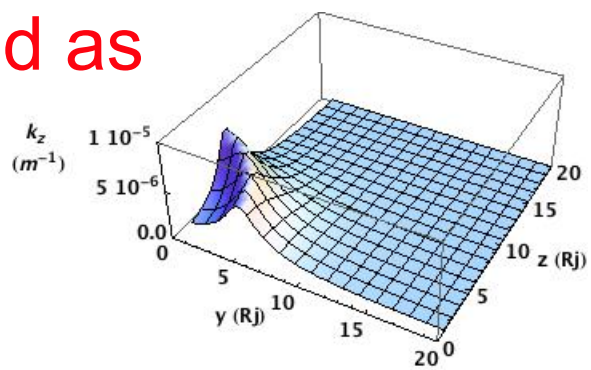
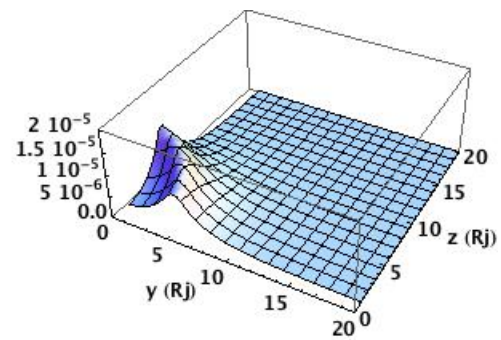
# Ray tracing initial conditions

- Spatial locations span a range of conditions
  - (2 Rj < r < 25 Rj)
- Corresponding wavelengths ($k_z$, $k_\perp$) calculated as function of position

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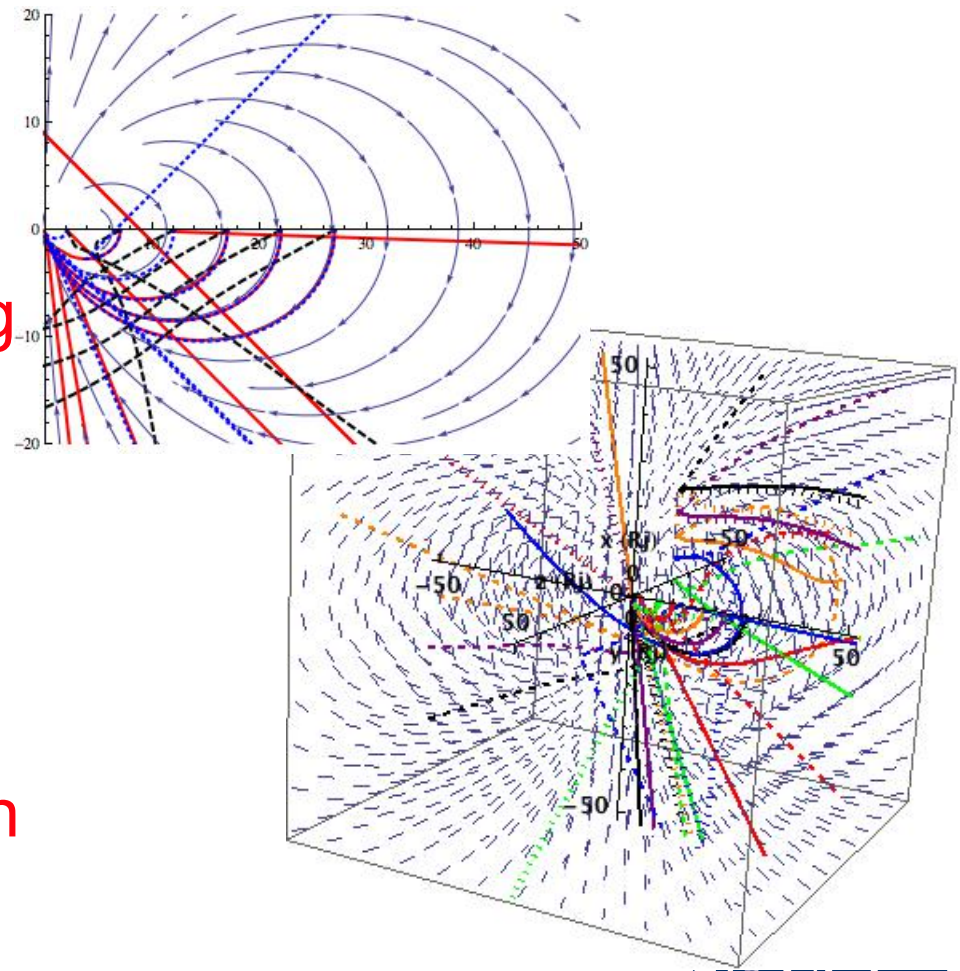
# Ray Tracing for Jovian Magnetosphere

- Initial $\omega$, $k_z$, $k_\perp$ determined from position
- Ray propagation adjusts with changing plasma and B parameters
- Parallel and perpendicular modes can appear.
- Some indications of resonance absorption

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# Antenna System

- Initial conditions indicate large antenna dimensions, ~ 10 – 100's km
- Some representative antenna in that size range have been modeled in the ANTENA code, using Jupiter magnetospheric B and density values
- Currently examining the effects of antenna size on coupling

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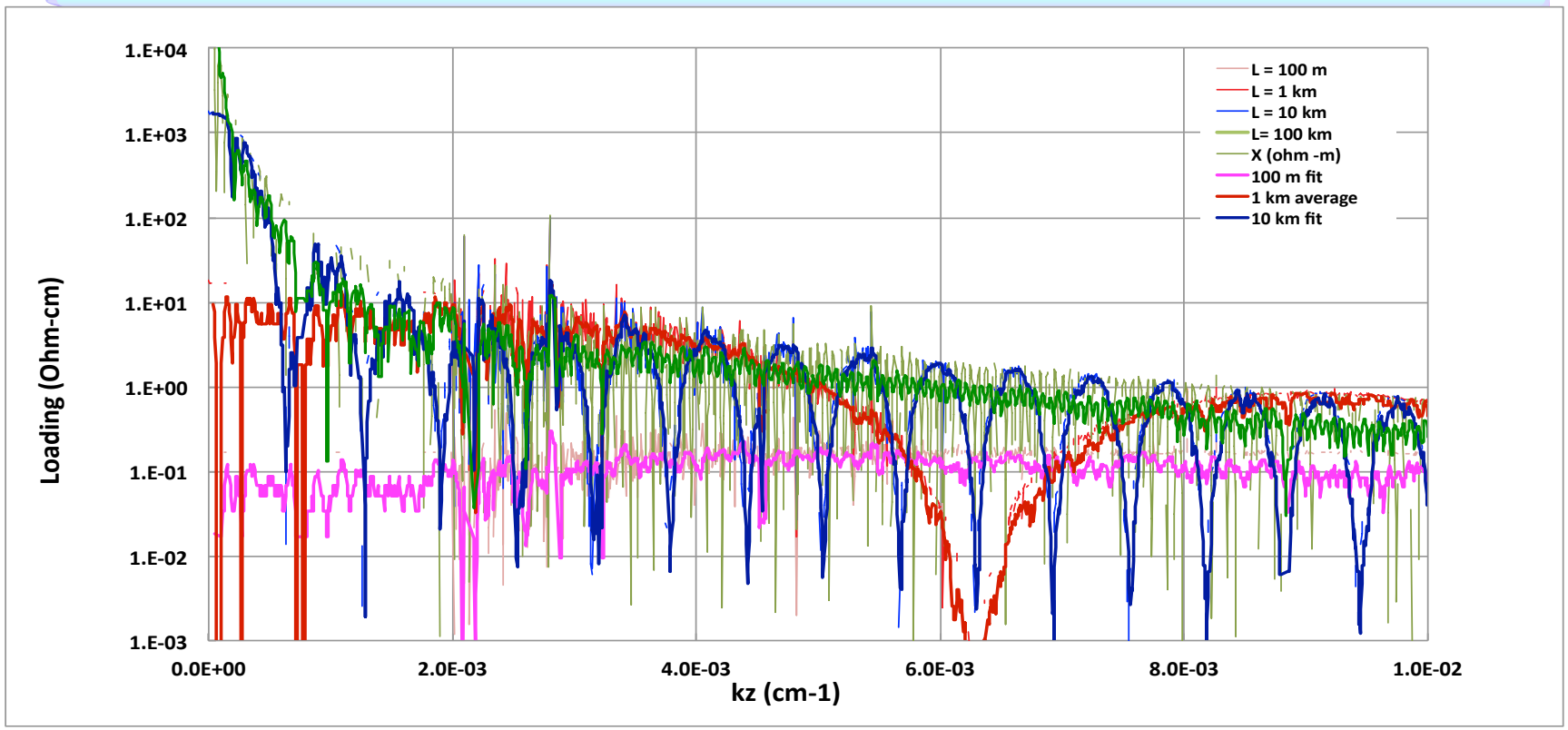
# Preliminary Antenna Length studies




- Assumes
  - Nagoya III antenna
  - Fixed diameter: 20 m
  - Vary length from 10 – 1000 km, examine antenna loading, power deposition with $k_z$

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# Early Observations

- Higher impedance occurs at small $k_z$
- Impedance inversely dependent on antenna length (fixed $k_\perp$)
  - Better coupling at 10 km < L < 100 km
  - 100 km length gives 10 X better coupling for Alfven waves
- Further optimization of $k_\perp$ to be done

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# Summary of Results

- Magnetosphere models have been developed
  - Jupiter, Earth
  - Solar requires modification to pure dipole model
- Ray tracing tool has been developed
  - Currently being applied to Jovian case
  - Results thus far are similar to previous analyses in the literature
- Antenna modeling tool is operating
  - Initial antenna sizing, loading is being conducted in parallel with ray tracing results

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# Future Work

- Conclude Jupiter case
  - Finalize wave propagation requirements
  - Find representative antenna designs and power requirements
- Repeat for Earth, Sun
  - Modify dipole for solar magnetic field model
- Estimate system performance
  - Thrust, Thrust vectoring, power
- Assess non-linear wave option

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