The Feasibility of Space Solar Power for Forward Operating Bases

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Overview

- *Interest in this study*
- Defining a Forward Operating Base (FOB)
- Discussion of FOB energy requirements and cost of this energy
- SSP in FOB applications
- Cost and savings analysis of using SSP
- Closing thoughts

Why Research This Topic?

- Countless examples of how technology progressed through military development, then trickled down to society
  - ENIAC, first programmable computer, developed by U.S. Army Research and Development Laboratory [1]
  - GPS
- If SSP were launched right now, the cost per kWh could not compete with what you pay at home
  - FOB application takes advantage of the enormous price of energy production to allow SSP to be able to compete in a niche market
  - SSP could then be proven successful/reliable = more funding = more development = lower costs = more general applications
- This technology could further U.S. military interests and has the potential to save lives

Overview

- A brief background of SSP
- *Defining a Forward Operating Base (FOB)*
- Discussion of FOB energy requirements and cost of this energy
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Forward Operating Bases

- DoD definition: “a facility used to support tactical operations without establishing full support facilities” [2]
- At peak of Afghanistan involvement, 400 FOBs existed in this country alone
  - More than 700 existed elsewhere around the globe [3]
- Main locations are Germany, Belgium, Japan, Africa, South Korea, and Middle East [3]
  - Establishes most FOBs below 60 degrees latitude – great for SSP accessibility
  - Assuming a stationary GEO satellite rather than a LEO constellation

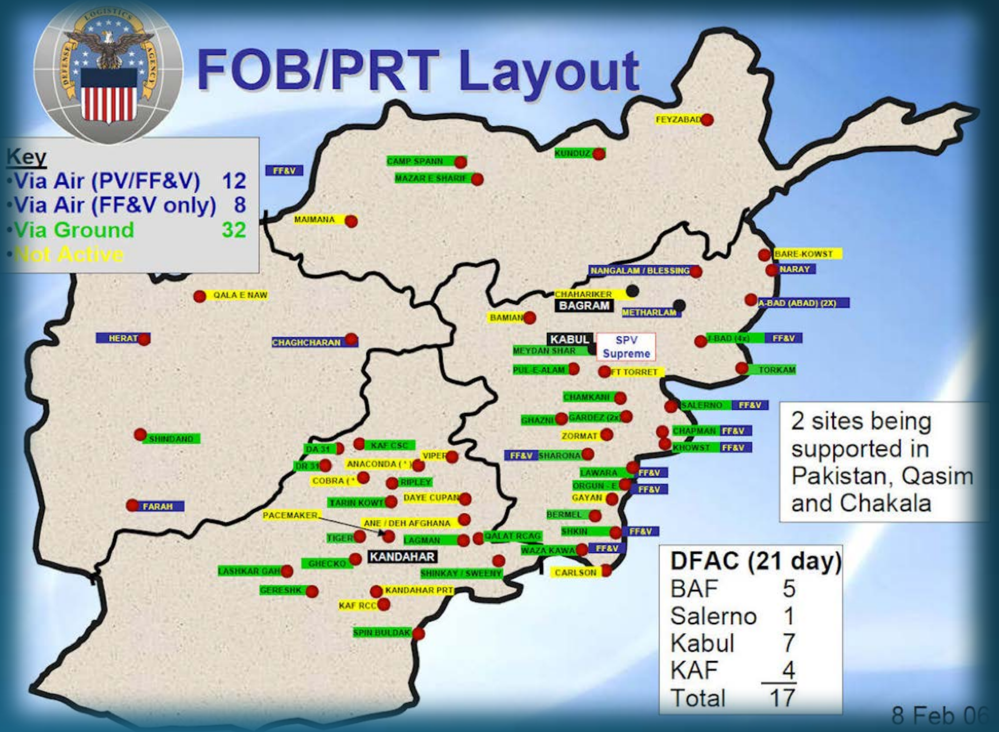

Image Credit: http://www.globalsecurity.org/military/facility/afghanistan.htm

How to Bound the Problem

- **People:** FOBs are designed to accommodate platoons and companies
  - Platoon = 25-60 soldiers [5]
  - Company = 70-250 soldiers [5]
- Other sources state 175 soldiers is a good average [6]
- **Consumption:** The continuous power consumption per soldier can range from 0.5 kW to 2 kW [5]
- **Duration:** Missions can range from a few weeks to 9 months
- **Transportation:** Several aircraft at their disposal [7]
  - MV-22 Osprey (vertical takeoff/landing) aircraft
  - KC130-J Super Hercules

Problem Now Bounded

- A reliable average for soldiers needing power is 175
- Lower estimates of 0.5-0.8 kW/person does not include HVAC
  - Use the upper estimate of 2 kW
  - (2 kW * 175 soldiers) + 50 kW margin = 400 kW continuous
- With power requirements known, mission duration can vary without impacting results of the study
- Assume 2 flights of the MV-22 Osprey to deliver SSP ground receiver with a possible 3rd for ground structure

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FOB Fuel Usage and Costs

- Monetary Cost
  - Study found the average fuel consumption per person per day is 4.3 gallons [5]
  - 4.3 gallons * 175 soldiers = 760 gallons per day
  - Bases primarily conducting ground operations use 78% of this for non-vehicle applications [5]
  - DoD estimates average cost of $45 per gallon, therefore one FOB could consume at least $26,676 worth of fuel per day for the 593 gallons needed for base support [5]
- Human Life Costs
  - 2007: 3,000 personnel killed or wounded in fuel or water delivery attempts [8]
  - 2010: U.S. Transportation Command estimates 1,100 ground convoy attacks [8]

FOB Battery Usage and Cost

- Not the primary source of power, however, they are used to support electronic equipment
- Weight increases due to 250% increase in radio usage and 300% increase in computer usage by U.S. Marines in recent years [8]
  - 2011: DoD estimates 10 lbs per soldier in their packs
  - 2012: Battery weight per person increases to 18 lbs
  - If trend continues, batteries will become prohibitively heavy
- Despite the weight of these batteries, most are used in personal packs on the move. SSP cannot solve this issue.

Image Credit: http://www.iamatechie.com/batteries-and-battery-chargers-for-field-infantry-electronics/6067

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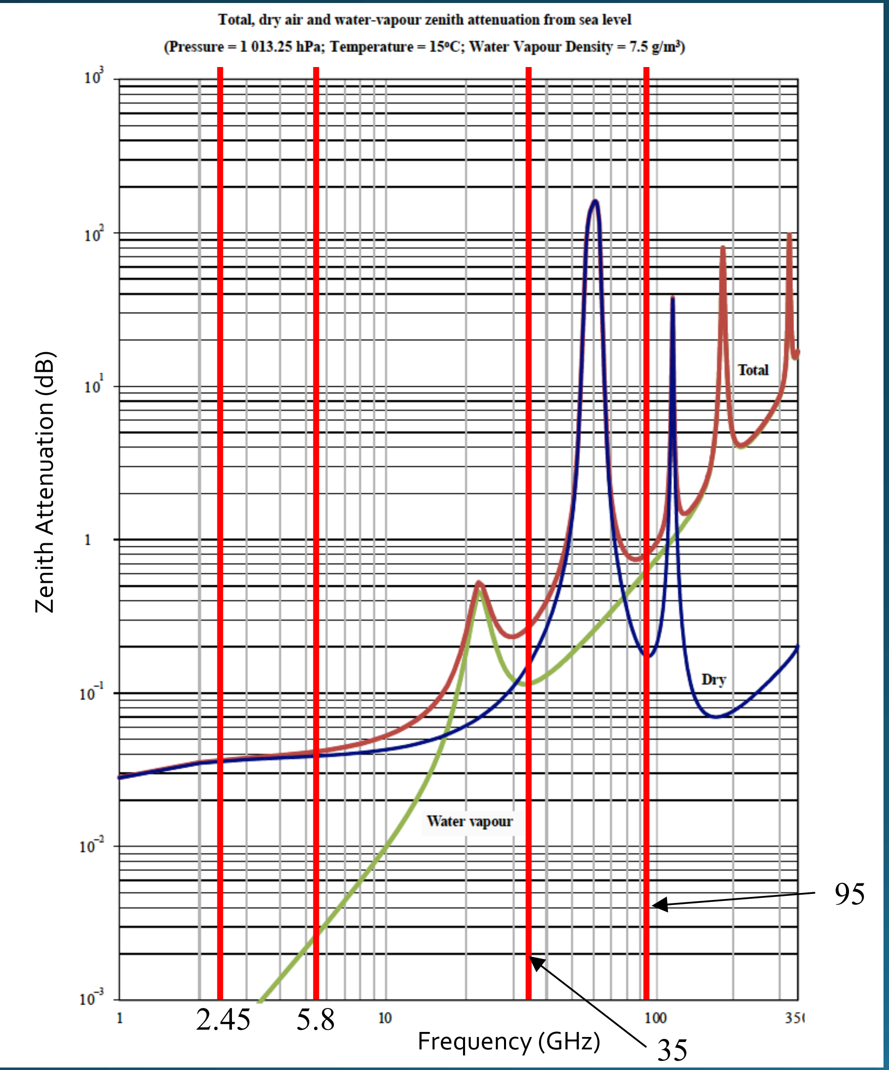
Microwave Power Transmission



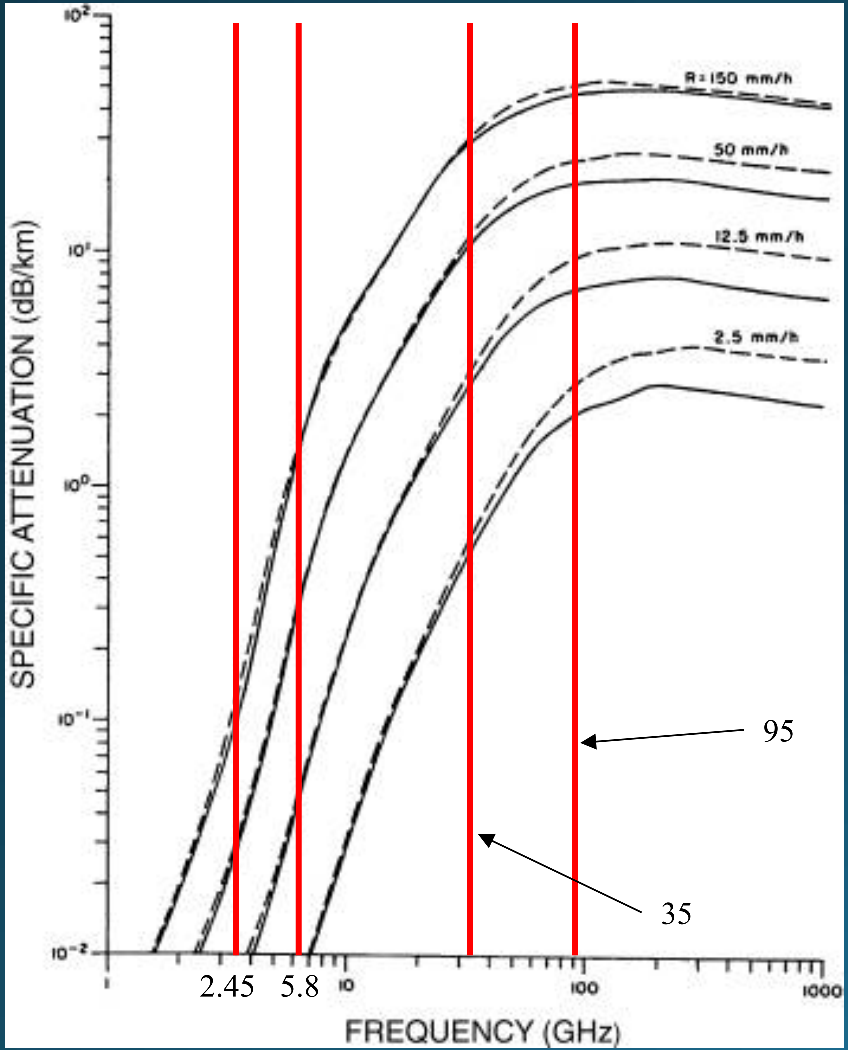
[9]

Atmospheric attenuation

- Zoomed in on microwave region
  - 1-350 GHz
- Minimal losses for lower frequencies

Note: 2.45 and 5.8 GHz fall within the industrial, scientific, and medical (ISM) radio bands

Microwave Power Transmission



[10]

Rain attenuation

- Minimal for lower frequencies
- Significant effect on 35 and 95 GHz frequencies

World Health Organization (WHO)

Adverse heath effects

- Occur at power densities over 1,000 W/m² for frequencies above 10 GHz
- Eye cataracts, skin burns

IEEE standard

- Safety factor of 10
- Recommended power densities
  - 300 – 3,000 MHz → $f_M/30$
  - 3,000 – 30,000 MHz → 100

Laser Power Transmission

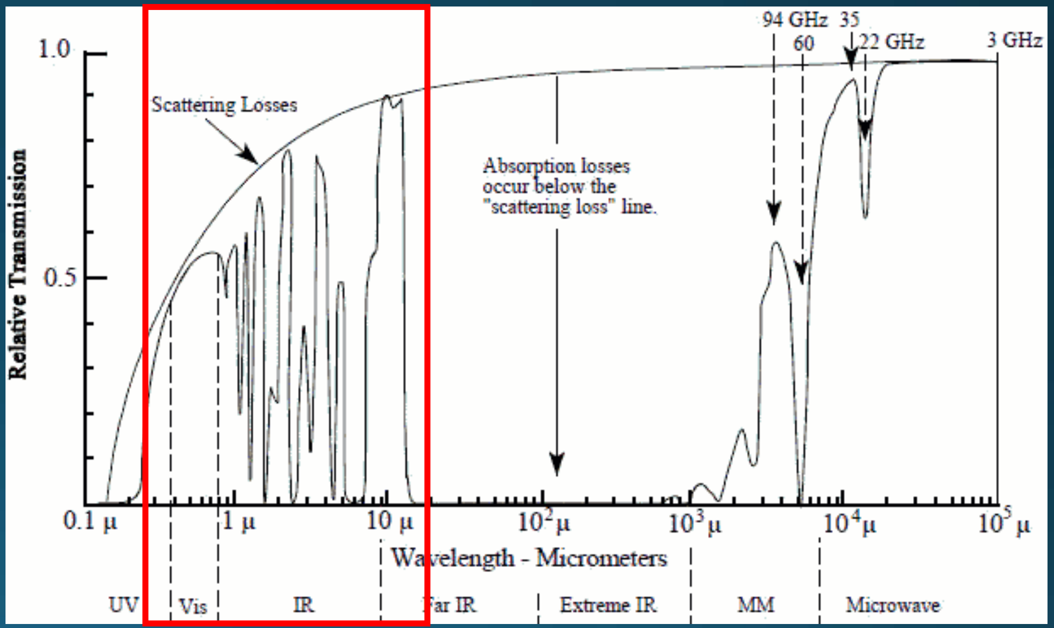
Two options looked at:

- IR and Visible

Significant scattering losses as the wavelength decreases

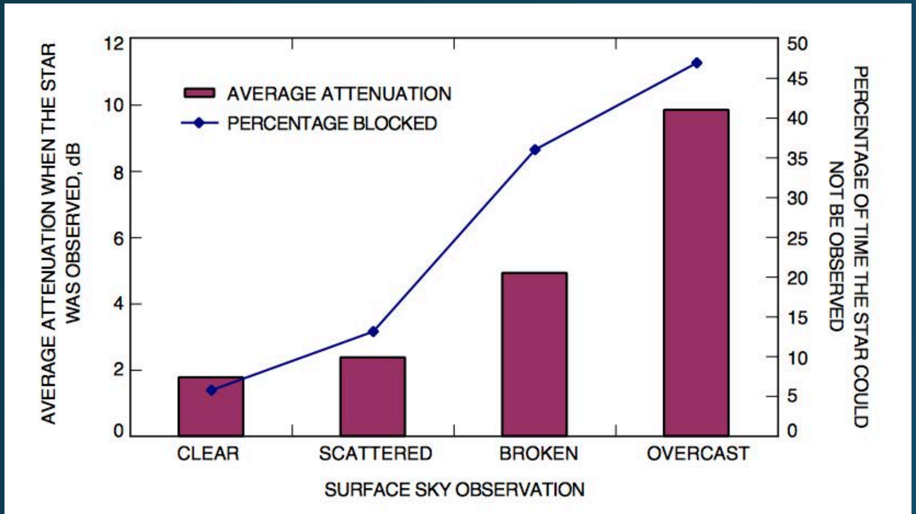
Lasers deal with much high power densities

- Need beam forming for efficiency

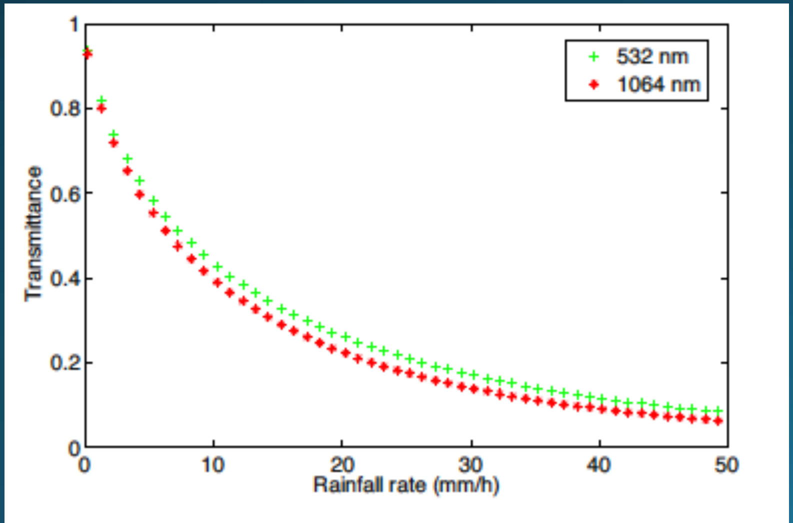


[11]

Laser Power Transmission



[12]



[13]

Weather has significant impact on laser transmission

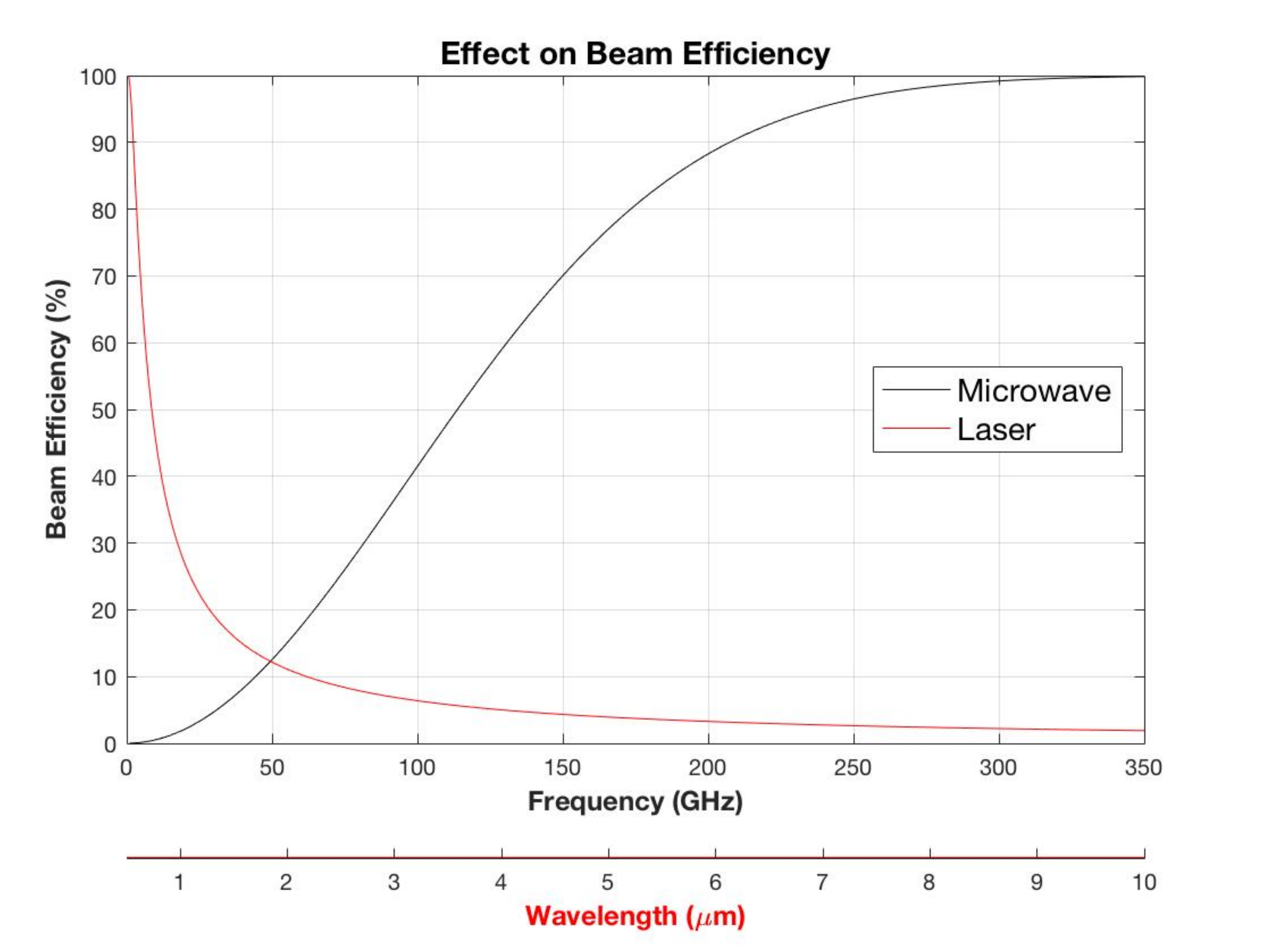
Infrared Energy Health Effects

- Cataracts – eye cannot detect IR
- Burns

Visible Energy Health Effects

- Indirect DNA damage through generation of reactive oxygen species

Receiver Size Trade Study



Note: Receiver efficiencies not accounted for in this plot

Assumptions:

Microwave
- Transmitter Area = 250,000 m^2
- Receiver Area = 24,667 m^2
  - Two MV-22 Osprey transports
  - Rectenna thickness of 1.5 mm [14]

Laser
- Transmitter Area = 200 m^2
- Receiver Area = 12.3 m^2

Geostationary Equatorial Orbit (GEO)

Use of Gobau and Schwering's Formulas

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Cost Analysis – Levelized Cost of Energy

SPS

$$\frac{Launch\,Cost(\$/kg) + System\,Cost(\$/kg)}{Mass\,Specific\,Power(W/kg) * Lifetime(hours)} = \$/kWh$$ [15]

Inputs	Case 1	Case 2	Case 3	Case 4
Mass-specific Power (W/kg)	5	40	250	500
Total Service Life (years)	20	20	20	20
Cost of Launch ($\$/kg$)	3,371	3,371	3,371	3,371
Cost of Space Segment ($\$/kg$)	10,000	2,000	500	100
Output				
Levelized Cost of Energy ($\$/kWh$)	15.25	0.77	0.09	0.04

Only changes in mass-specific power and cost of space segment allowed

Launch cost will likely decrease

FOB

$26,676 for fuel per day

1 gallon ≈ 40.7 kWh

Assumed 45% efficiency

→ 18.32 kWh/gallon

593 gallons → 10,861 kWh

Levelized cost for FOB

→ 2.46 $/kWh

Case 1 – Current technology

Case 2 – 5 years in the future

Case 3 – 10 years in the future

Case 4 – further in the future

Cost Analysis – Savings to Human Life

- As stated, 3,000 soldiers killed or injured annually in convoys
- 80% of truck convoys supply fuel to FOBs [5]
  - As mentioned, up to 78% of fuel is what can be saved by using an SSP concept
  - 3,000 * 80% * 78% = 1872 soldiers
- Any technology that has the ability to reduce potential casualties regarding a certain operation by up to 62% deserves serious consideration
- Safe to assume that the cost of human life vastly outweighs any monetary cost
  - Automatic death gratuity of $100,000 – $800,000 per person [16]
  - 1,872 people equates to $187.2 million – $1.5 billion annually

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- *Closing thoughts*

Summary-MPT

- Ground receiving array size is fixed
- A small transmitting array leads to poor transmission efficiency and low power densities
- MPT frequencies above 5.8 GHz become more susceptible to atmospheric and rain attenuation
  - Major advantage over laser since military operations cannot cease simply due to rain
- One feasible solution for MPT is 95 GHz since transmitter array size increases as microwave frequency decreases
  - Going to have attenuation
  - 2.45 and 5.8 GHz produce prohibitively large transmitter arrays
  - Assumed fixed receiver size of 24,667 m^2 – two MV-22 Osprey transports
    - Rectenna thickness of 1.5 mm [14]
  - One goal of FOB application is to reduce all hardware sizes

Summary-Laser

- Ground receiving array size is fixed
- Significantly smaller transmitting array sizes while maintaining high beam efficiency
- Subject to scattering and attenuation effects in the atmosphere, especially in poor weather
  - Could be mitigated by having the SSP system also charge a reserve battery supply
- One very feasible solution is a 2.1 micron beam with a transmitting area of 20 m^2 and a receiver area of 500 m^2
  - 500 m^2 much lower than the 24,667 m^2 from two MV-22 Osprey transports
    - Assumed a rectenna thickness of 1.5 mm [14]

Future Work

- Look at weight/options for ground antenna structure
  - Excessive structural mass could disprove this study's 1 flight assumption
  - This could be another reason for laser as the best option
- Look at more in depth design of space platform
  - What would the overall size of a space satellite be with solar panels and other structure?
  - Will likely still follow the scaled size assumption discussed
- Gain an even better understanding of military standards
  - Does the military have different (higher) allowable power density health standards?
  - How does frequency allocation work in strictly military applications?
- Geopolitical Effects
  - How do other countries feel about potential high power lasers being used for the U.S. military on foreign soil?

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Thank you!
Questions?

Image Credit: http://www.marforaf.marines.mil/News/News-Article-Display/Article/520559/marines-test-out-alternative-energy-system-at-african-lion/

Appendix

Image Credit: http://www.marforaf.marines.mil/News/News-Article-Display/Article/520559/marines-test-out-alternative-energy-system-at-african-lion/

Receiver Size Trade Study

	Frequency	λ (m)	A_t (m^2)	A_r (m^2)	% Efficiency	P_t	Power Density (W/m^2)
Microwave Region	2.45 GHz	0.1224	100,000	24,667	0.01286	3.1 GW	16.2
	5.8 GHz	0.0517	100,000	24,667	0.07207	0.56 GW	16.2
	35 GHz	8.565e-3	100,000	24,667	2.591	15 MW	16.4
	95 GHz	3.156e-3	100,000	24,667	17.59	2.3 MW	17.8
Laser Region	30 THz	10e-6	20	500	7.51	5.3 MW	831
	143 THz	2.1e-6	20	500	82.98	482 kW	1,707
	300 THz	1e-6	20	500	99.96	400.2 kW	6,249
	599.6 THz	500e-9	20	500	100	400 kW	24,988

Fixed transmitter and receiver area

- MV-22 Osprey Cargo Capacity – 18.5 m^3
  - Assumed entire cargo bay
- Rectenna thickness – 1.5 mm
- Use of Gobau and Schwering's Formulas

Beam Efficiency (%)

- Does not account for receiver efficiency

Receiver Size Trade Study

	Frequency	λ (m)	A_t (m^2)	A_r (m^2)	% Efficiency	P_t (kW)	Power Density (W/m^2)
Microwave Region	2.45 GHz	0.1224	2.5e9	24,667	96	416.7	54.4
	5.8 GHz	0.0517	4.5e8	24,667	96	416.7	54.4
	35 GHz	8.565e-3	1.2e7	24,667	96	416.7	54.4
	95 GHz	3.156e-3	1.7e6	24,667	96	416.7	54.4
Laser Region	30 THz	10e-6	3.3e4	12.3	96	416.7	108,750
	143 THz	2.1e-6	1,474	12.3	96	416.7	108,750
	300 THz	1e-6	334	12.3	96	416.7	108,750
	599.6 THz	500e-9	84	12.3	96	416.7	108,750

Fixed receiver area and efficiency

- MV-22 Osprey Cargo Capacity – 18.5 m^3
  - Assumed entire cargo bay
- Rectenna thickness – 1.5 mm
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Beam Efficiency (%)

- Does not account for receiver efficiency

Relevant Equations

Gobau and Schwering's Formulas

Beam efficiency

$$\eta = 1 - e^{-\tau^2}$$

τ parameter and power density (pd)

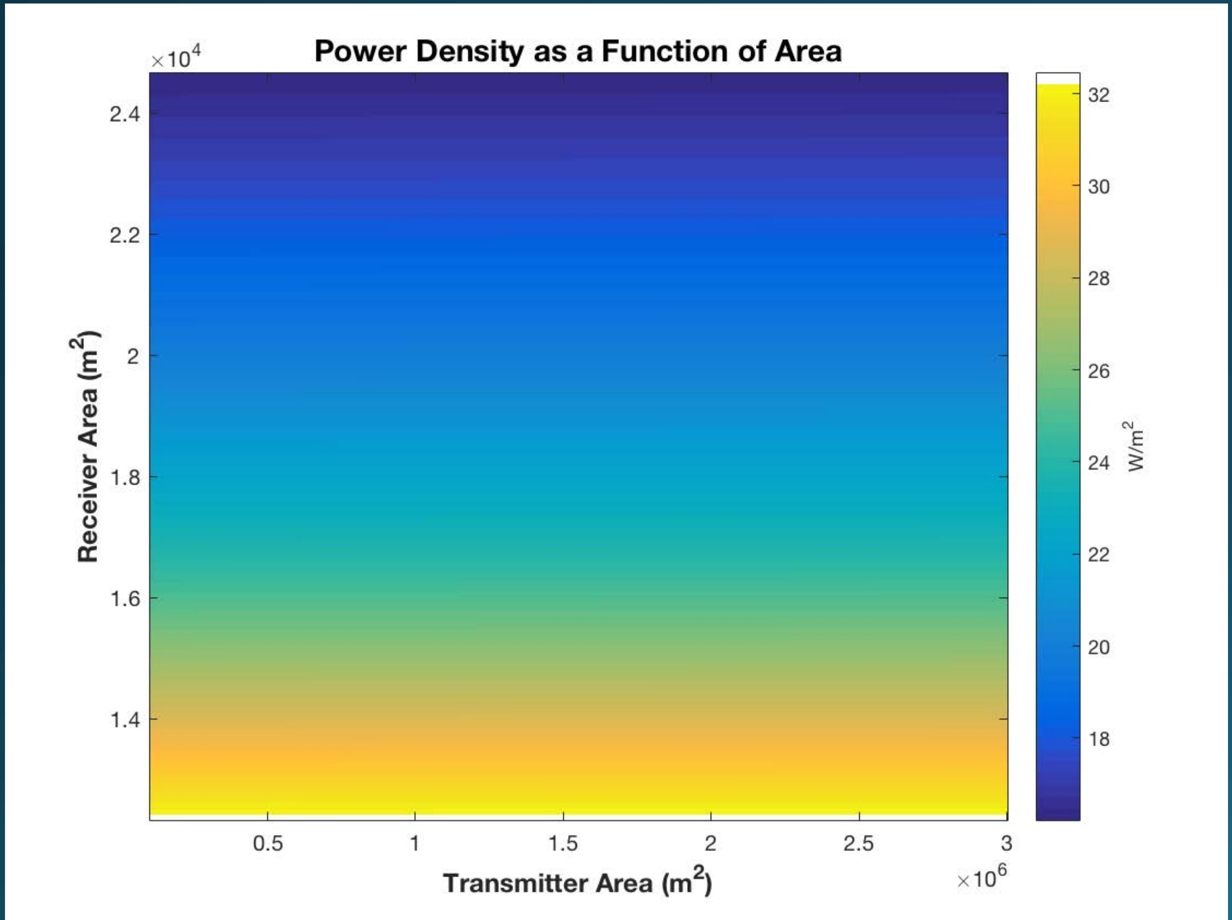
$$\tau^2 = \frac{P_r}{P_t} = \frac{A_t A_r}{\lambda^2 d^2} \rightarrow pd = \frac{P_r}{A_r} = \frac{A_t P_t}{\lambda^2 d^2}$$

Where

λ - wavelength, A_t – transmitter area,

A_r – receiver area, d - distance

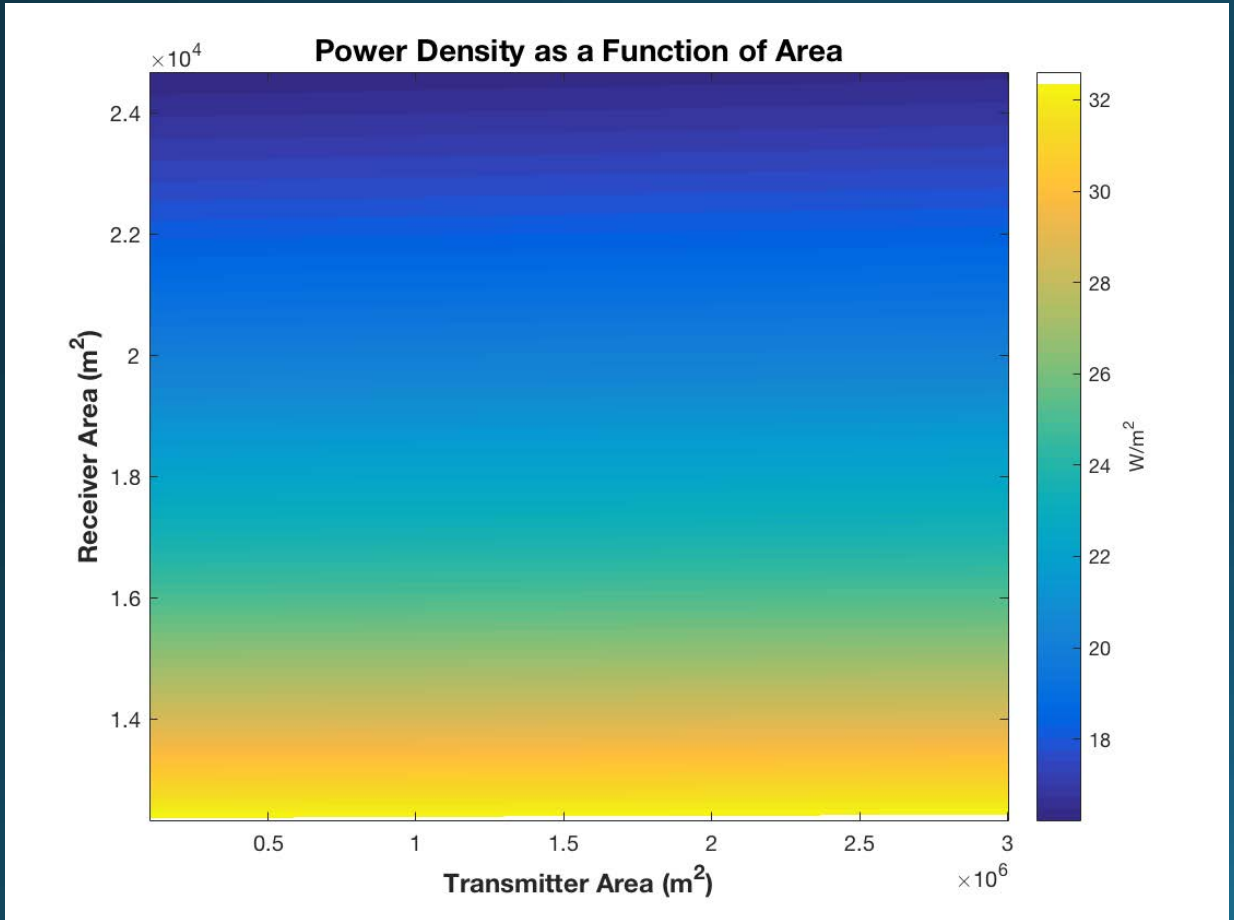
Power Density – MPT – 2.45 GHz



Assumptions:

- Transmitter area allowed to vary from 100,000 m^2 to 3,000,000 m^2
- Receiver area allowed to vary from 12,333 m^2 to 24,667 m^2
  - 1-2 MV-22 Osprey flights
- GEO
- Ideal receiver efficiencies
- Use of Gobau and Schwering's Formulas

Power Density – MPT – 5.8 GHz



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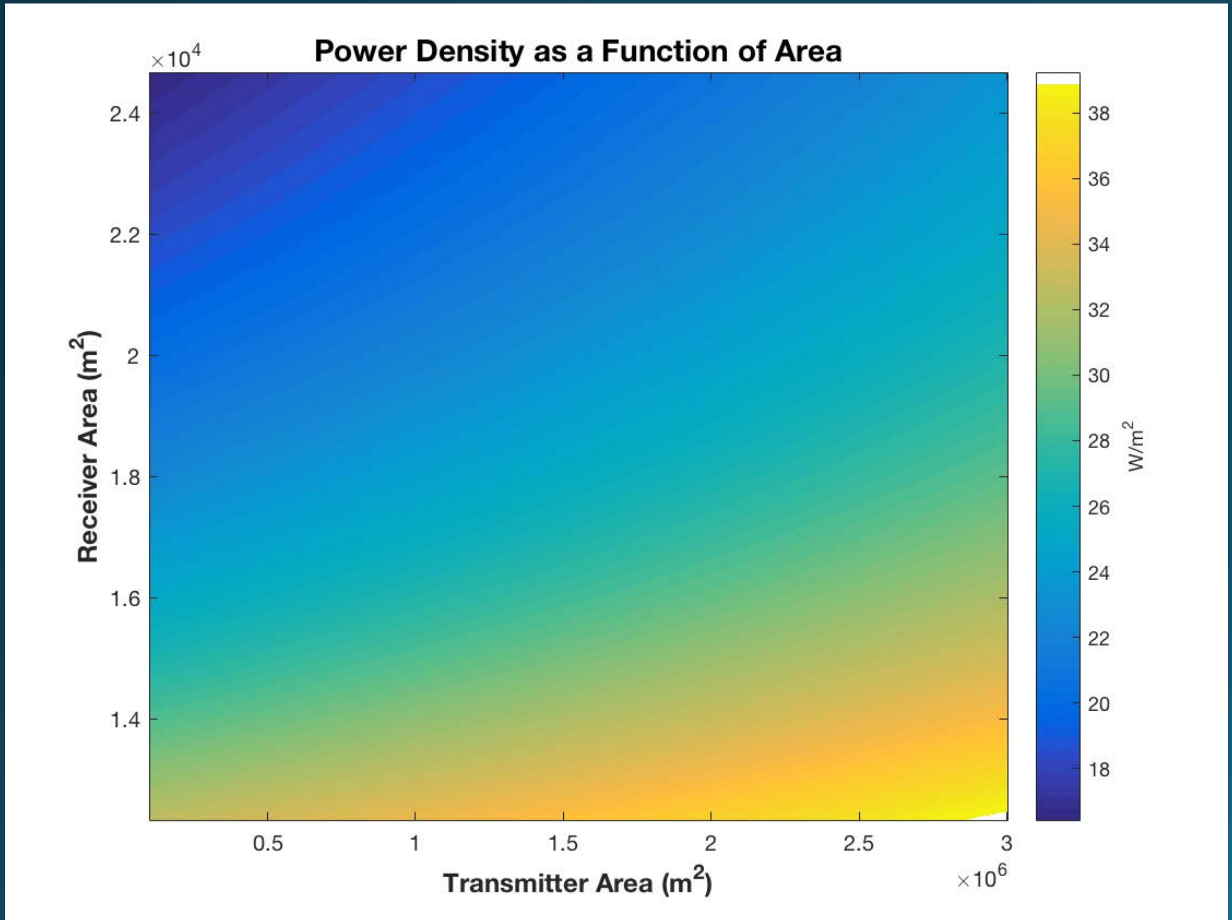
Power Density – MPT – 35 GHz



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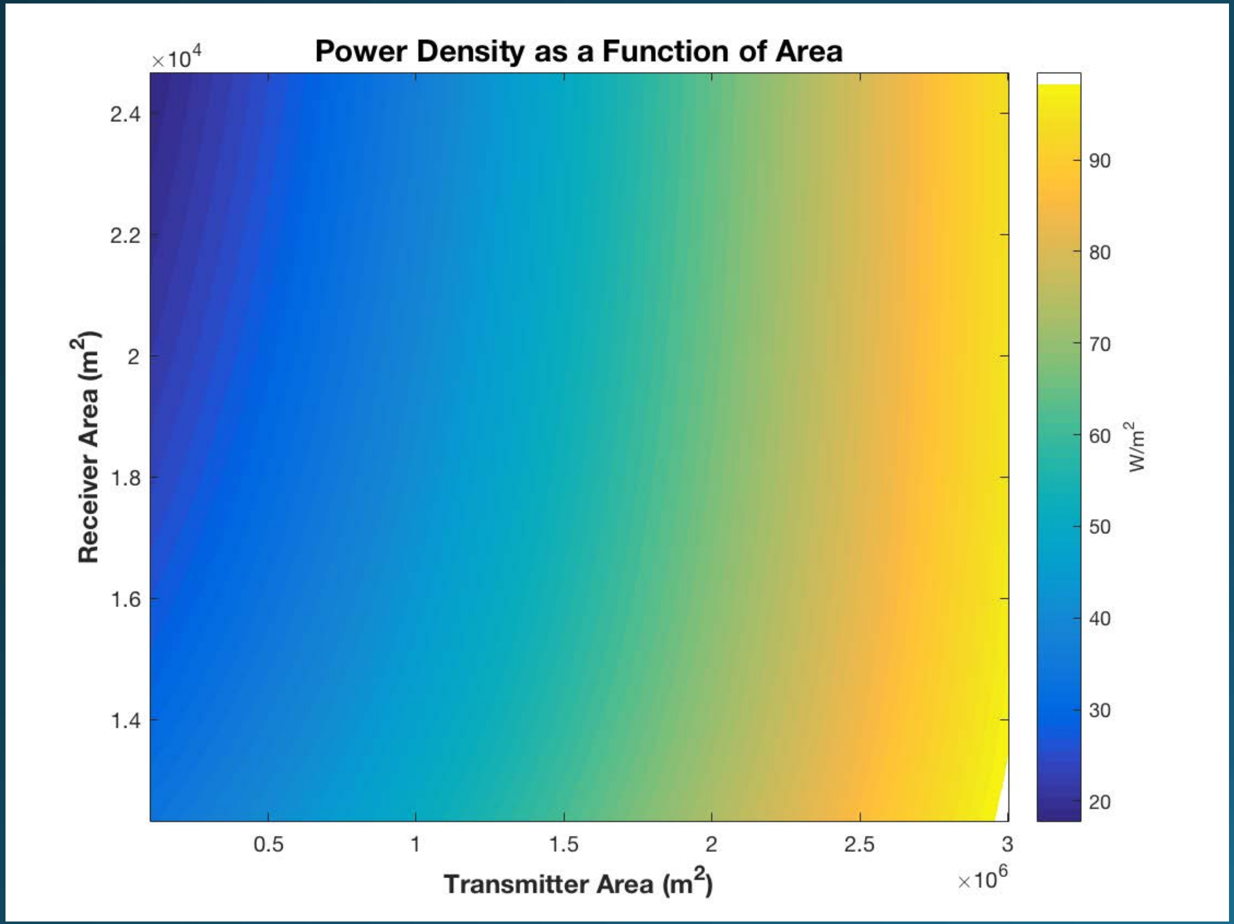
Power Density – MPT – 95 GHz



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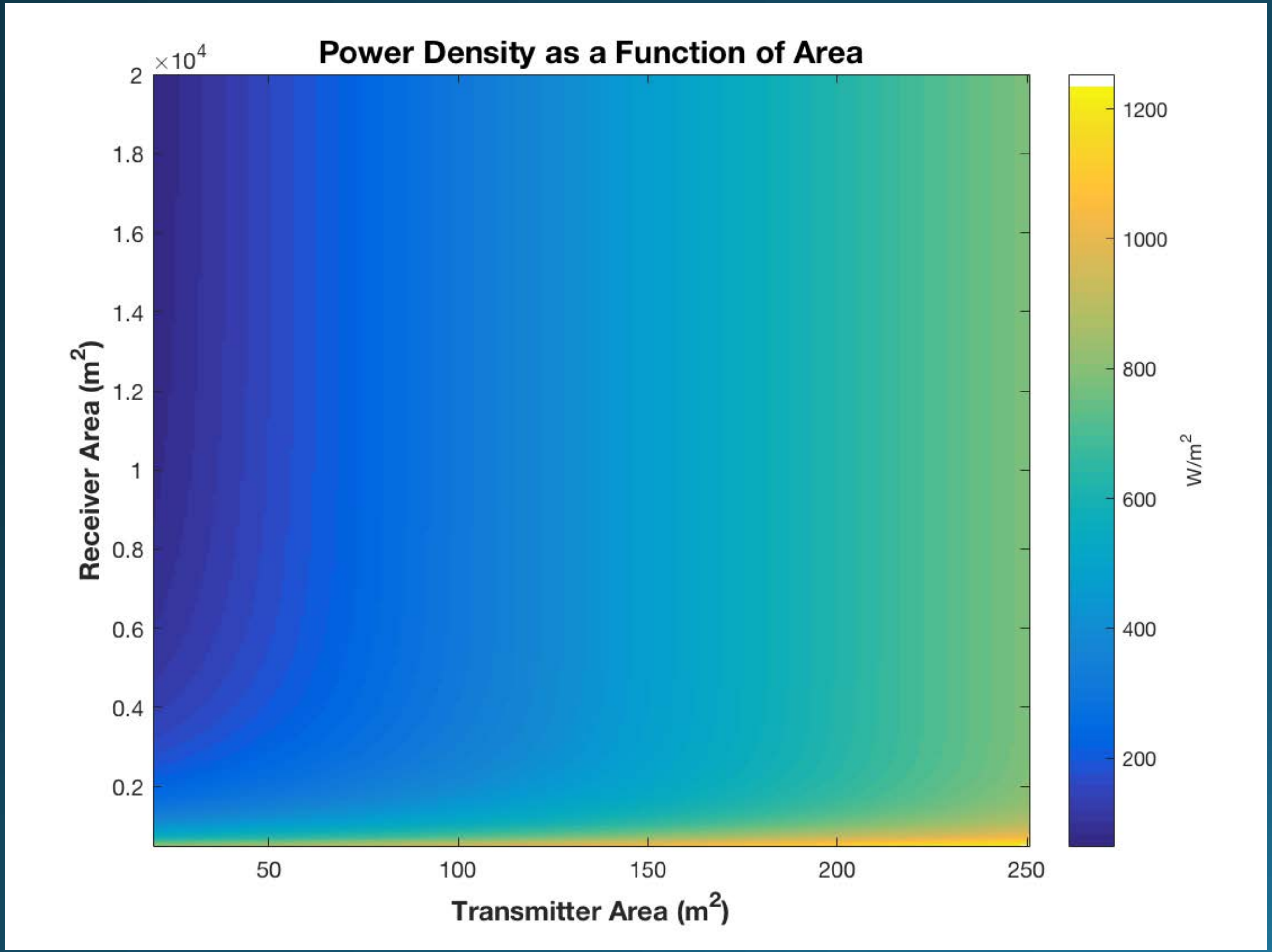
Power Density – Laser – 10 μm



Assumptions:

- Transmitter area allowed to vary from 500 m² to 20,000 m²
- Receiver area allowed to vary from 20 m² to 250 m²
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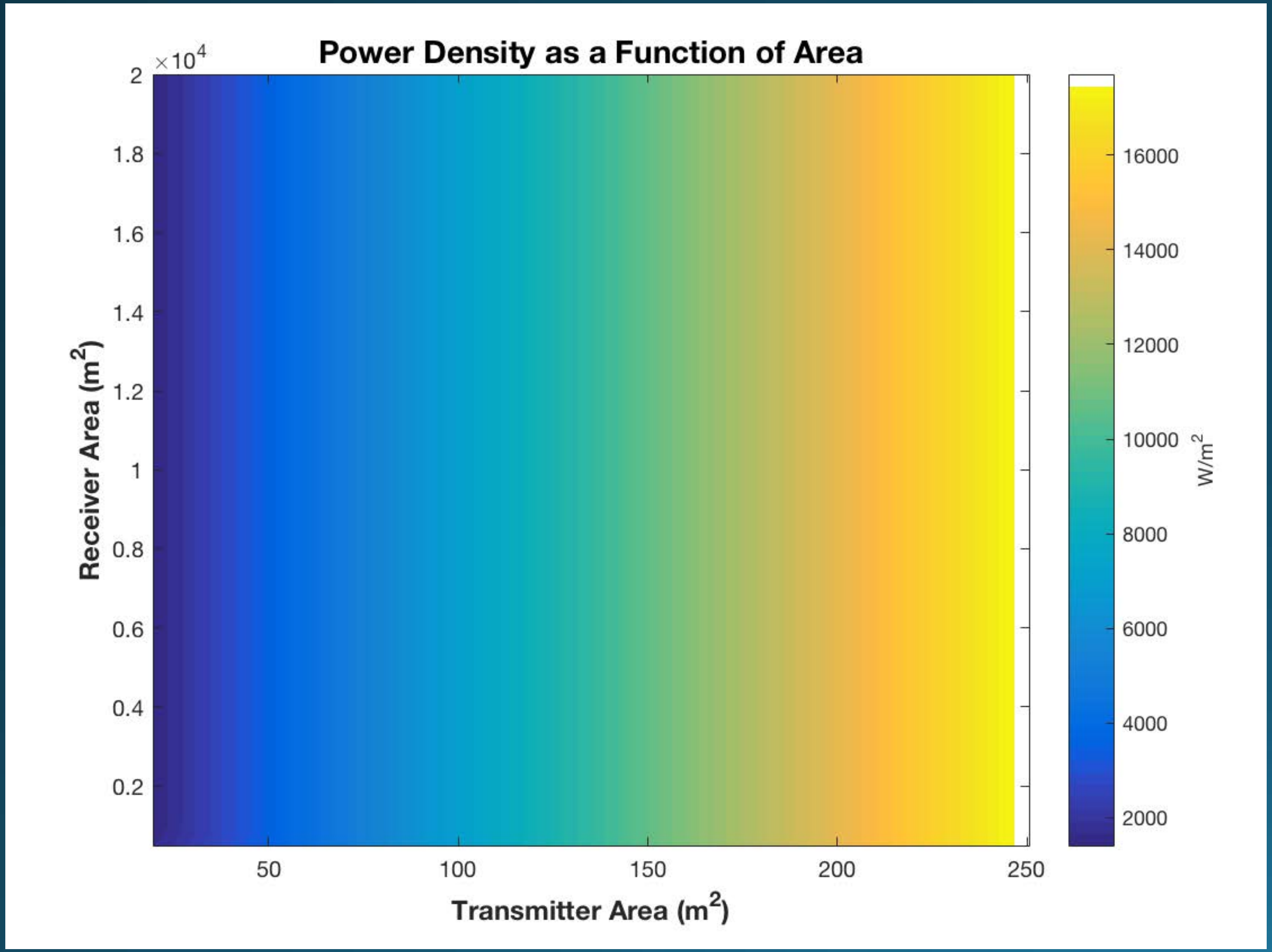
Power Density – Laser – 2.1 μm



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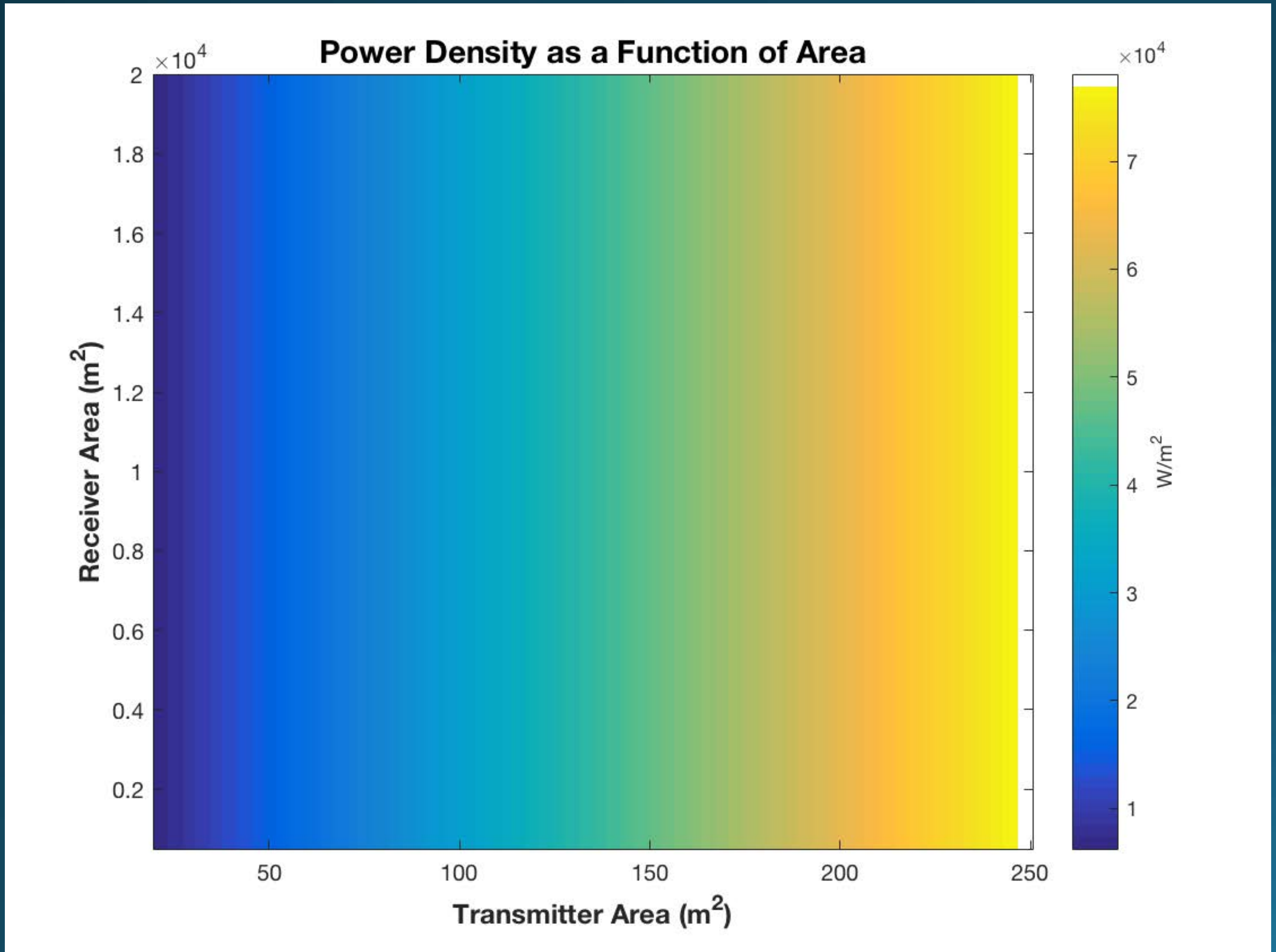
Power Density – Laser – 1 μm



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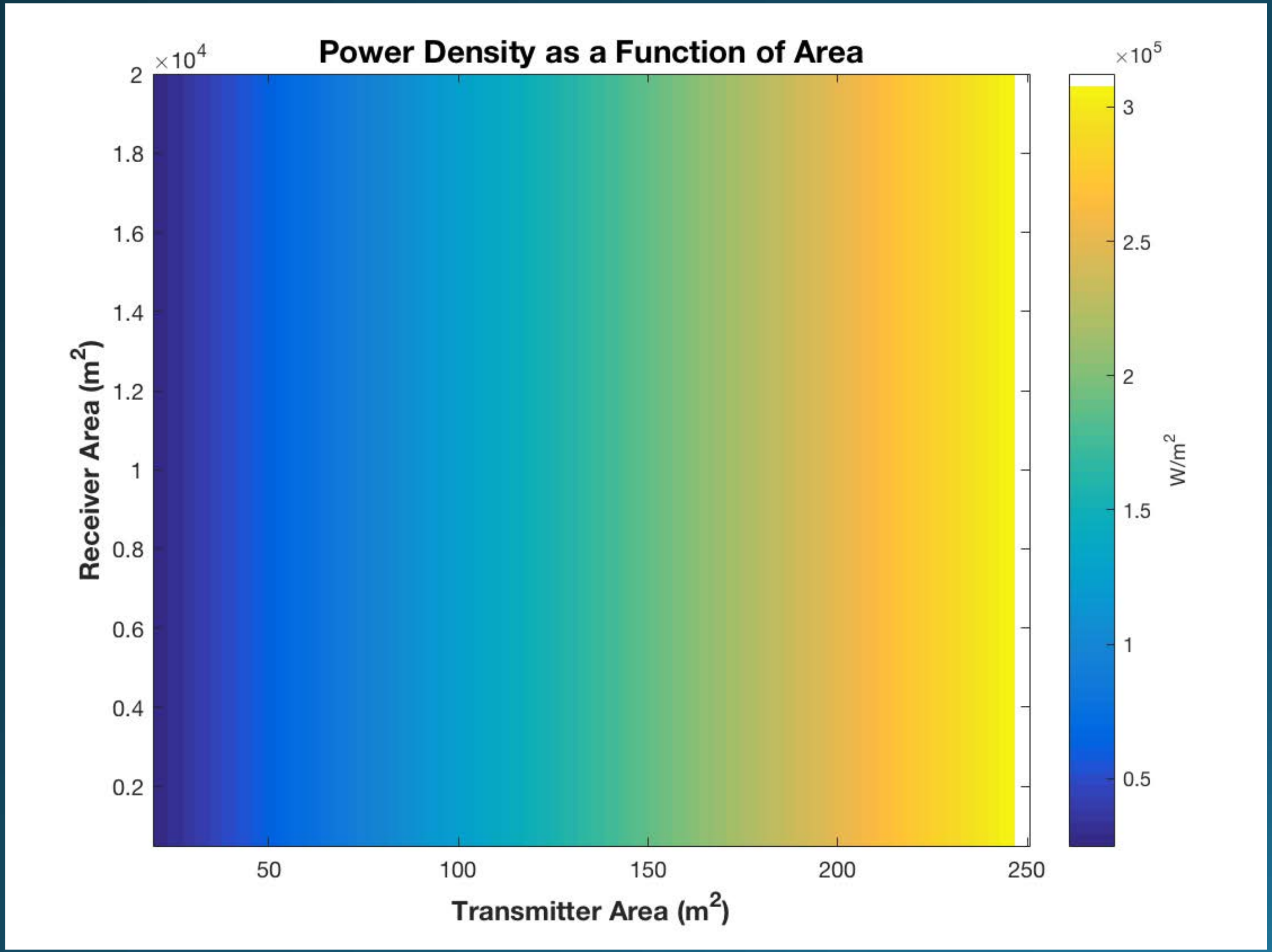
Power Density – Laser – 500 nm



Assumptions:

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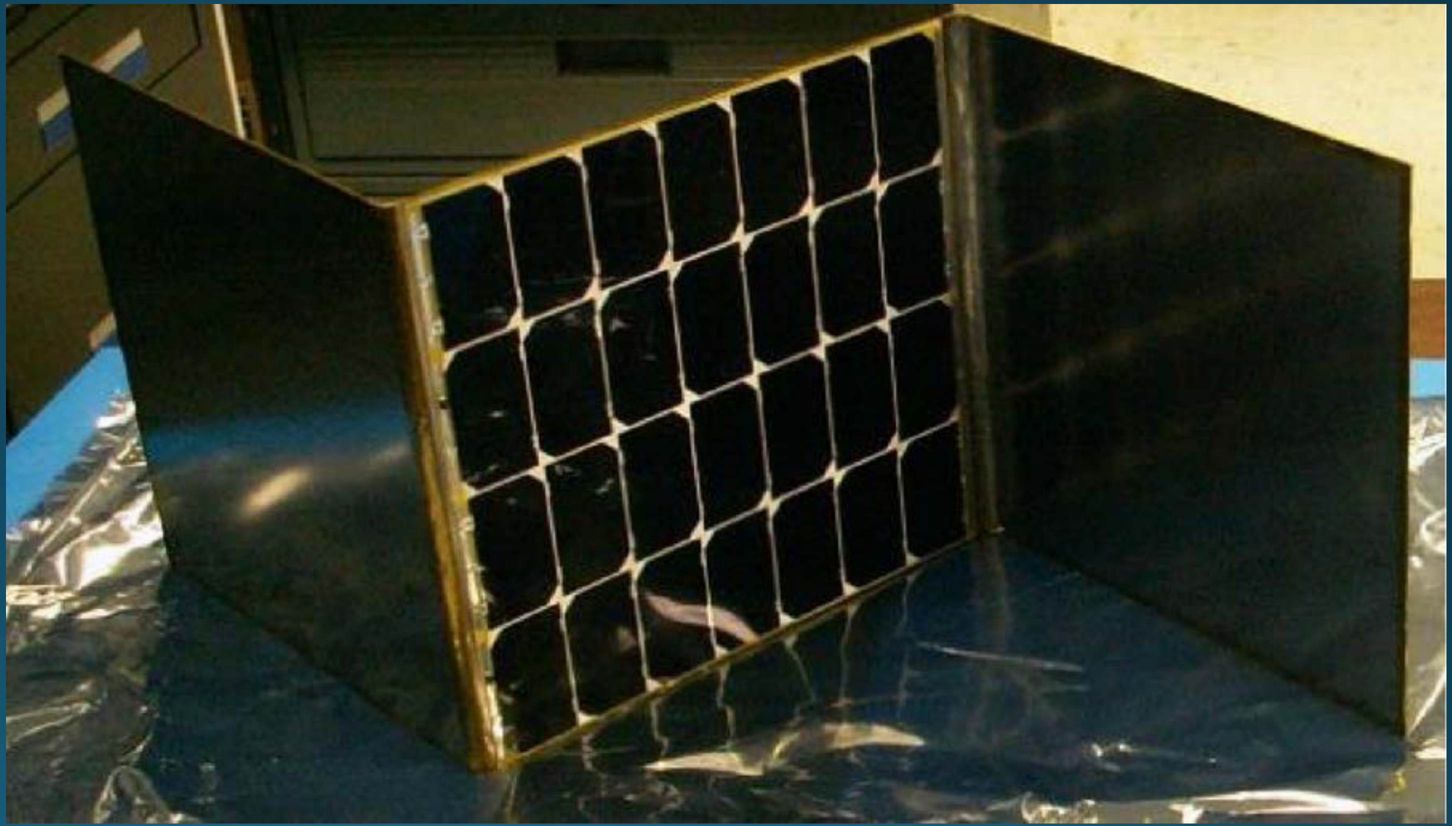
NRL Sandwich Module

Mass specific power

Ambient conditions

- 7.8 W/kg – one sun concentration
- 13.8 W/kg – three suns concentration



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SpaceX Launch Costs

Capabilities & Services | SpaceX

CAPABILITIES & SERVICES

SpaceX offers competitive pricing for its Falcon 9 and Falcon Heavy launch services. Modest discounts are available, for contractually committed, multi-launch purchases. SpaceX can also offer crew transportation services to commercial customers seeking to transport astronauts to alternate LEO destinations.

PRICE	FALCON 9	FALCON HEAVY
STANDARD PAYMENT PLAN (2018 LAUNCH)	$62M Up to 5.5 mT to GTO	$90M Up to 8.0 mT to GTO

DESTINATION	PERFORMANCE*	PERFORMANCE*
LOW EARTH ORBIT (LEO)	22,800 kg 50,265 lbs	63,800 kg 140,660 lbs
GEOSYNCHRONOUS TRANSFER ORBIT (GTO)	8,300 kg 18,300 lbs	26,700 kg 58,860 lbs
PAYLOAD TO MARS	4,020 kg 8,860 lbs	16,800 kg 37,040 lbs

*Performance represents max capability on fully expendable vehicle

Inclination: LEO = 28.5°, GTO = 27°

http://www.spacex.com/about/capabilities

Cost Analysis – Levelized Cost of Energy

Inputs	Case 1	Case 2	Case 3	Case 4
Mass-specific Power (W/kg)	5	40	250	500
Total Service Life (years)	20	20	20	20
Cost of Launch ($\$/kg$)	3371	3371	3371	3371
Cost of Space Segment ($\$/kg$)	10,000	10,000	10,000	10,000
Output				
Levelized Cost of Energy ($\$/kWh$)	15.25	1.91	0.31	0.15

Falcon 9 Heavy Launch Costs
Constant Cost of Space Segment

http://www.spacex.com/about/capabilities

Cost Analysis – Levelized Cost of Energy

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Cost of Space Segment ($\$/kg$)	20,000	10,000	5,000	2,500
Output				
Levelized Cost of Energy ($\$/kWh$)	26.66	1.91	0.19	0.07

Falcon 9 Heavy Launch Costs

http://www.spacex.com/about/capabilities