Wireless Power Transmission Options for Space Solar Power

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Abstract for a presentation to be given at the
State of Space Solar Power Technology Workshop
Lake Buena Vista, Florida
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Space Solar Power (SSP), combined with Wireless Power Transmission (WPT), offers the far-term potential to solve major energy problems on Earth. In the long term, we aspire to beam energy to Earth from geostationary Earth orbit (GEO), or even further distances in space. In the near term, we can beam power over more moderate distances, but still stretch the limits of today's technology. In recent studies, a 100 kWe-class "Power Plug" Satellite and a 10 kWe-class Lunar Polar Solar Power outpost have been considered as the first steps in using these WPT options for SSP. Our current assessments include consideration of orbits, wavelengths, and structural designs to meet commercial, civilian government, and military needs. Notional transmitter and receiver sizes are considered for use in supplying 5 to 40 MW of power. In the longer term, lunar or asteroidal material can be used. By using SSP and WPT technology for near-term missions, we gain experience needed for sound decisions in designing and developing larger systems to send power from space to Earth.

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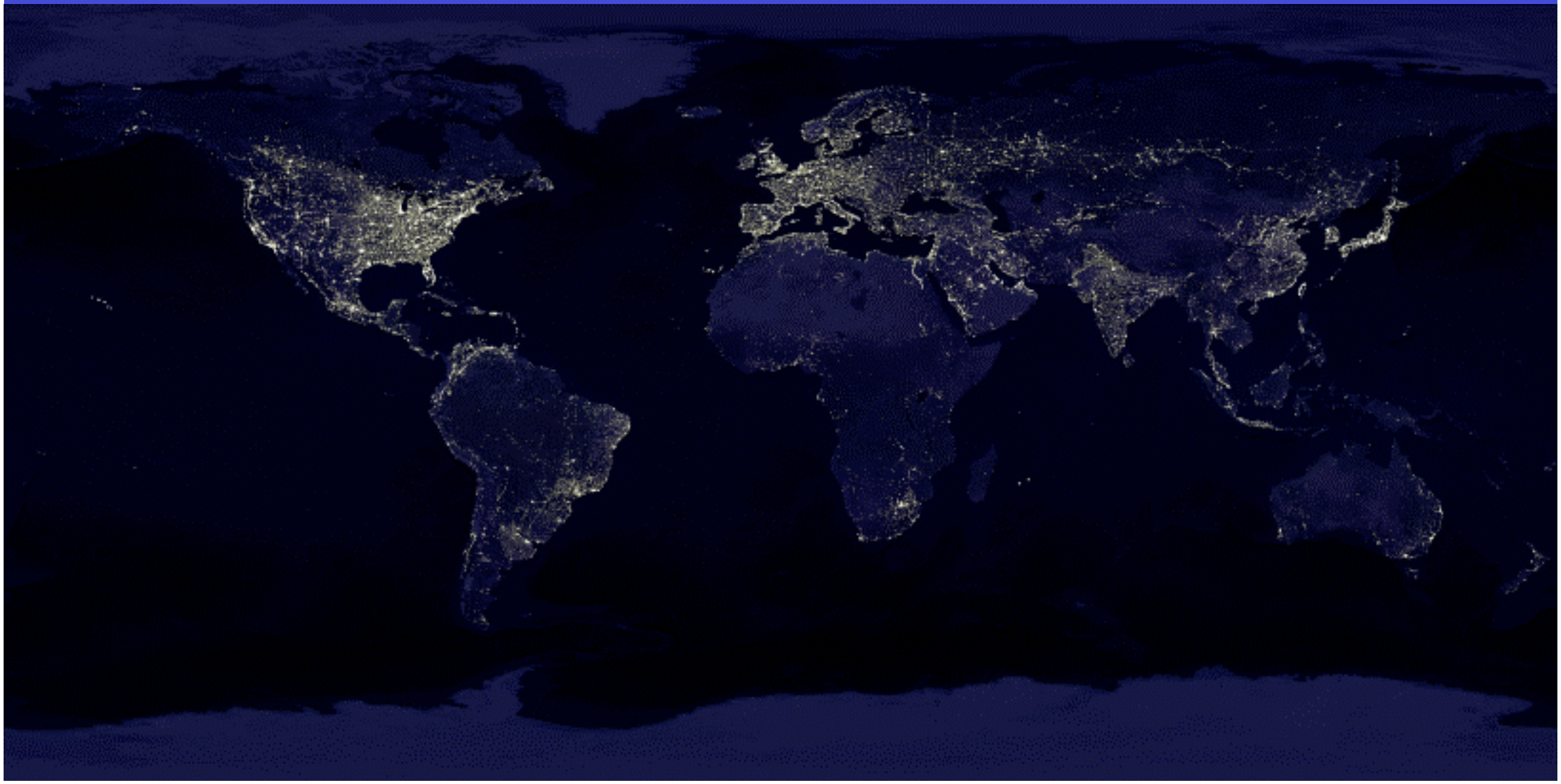
Global Power Consumption



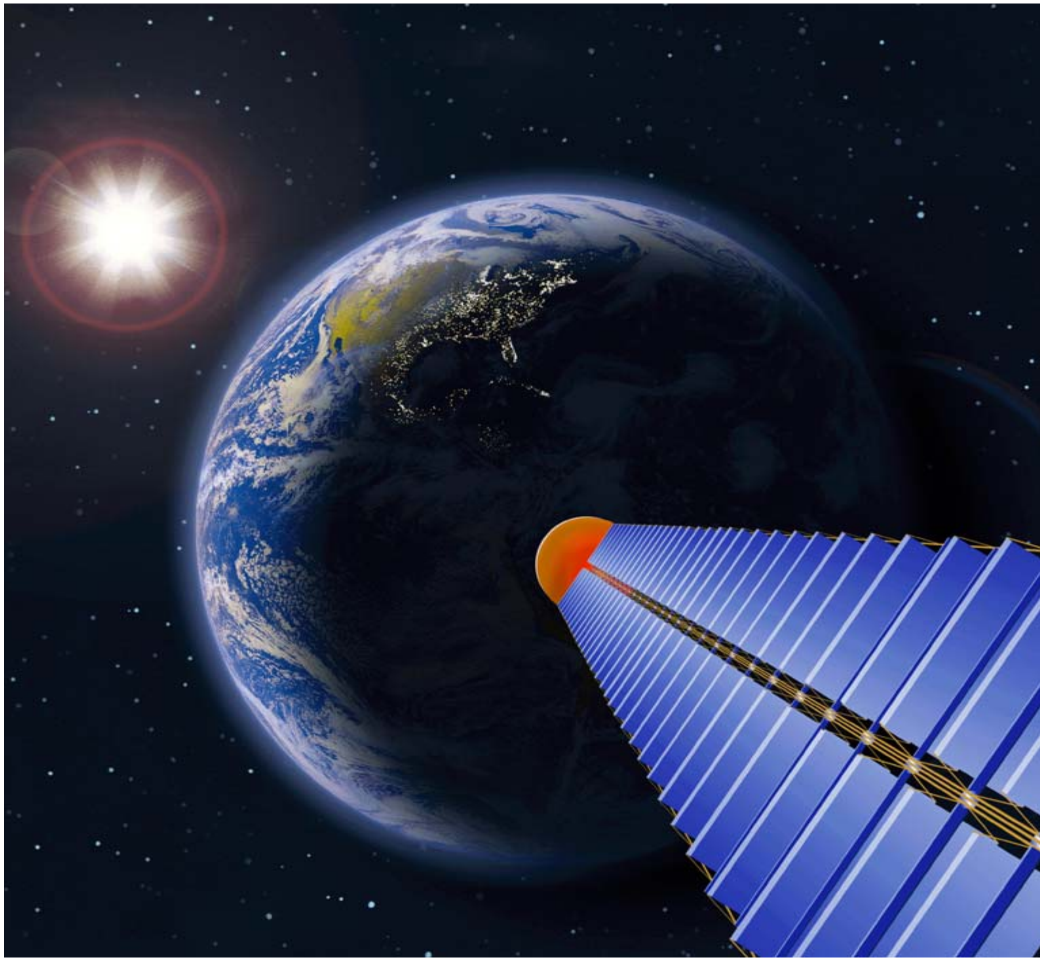
Remote Sensing of Current Global Power Consumption:
A Composite Satellite Photograph of the Earth at Night

Wireless Power Transmission Options for Space Solar Power: Previous Studies at Boeing and NASA

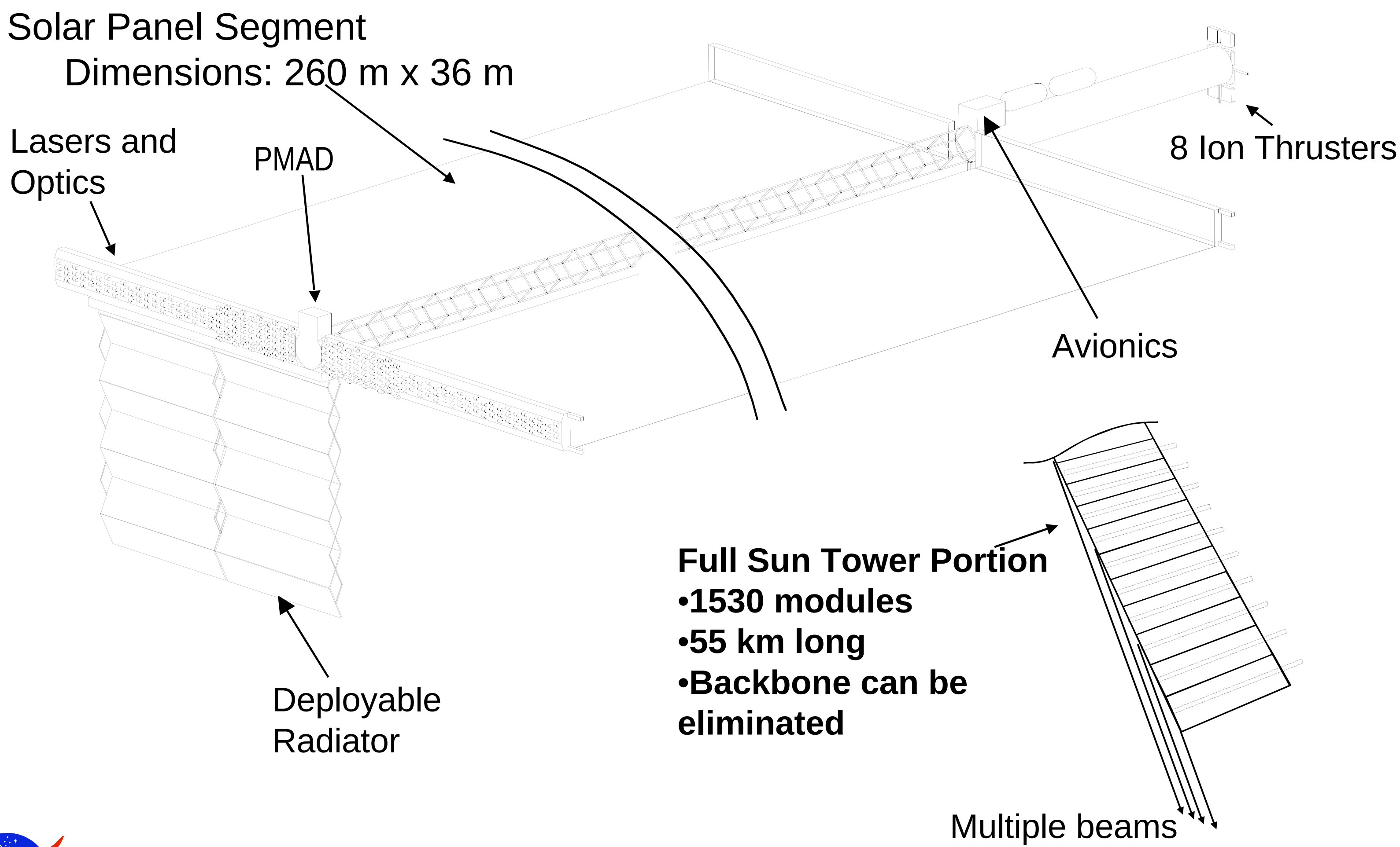
- Far Term Space Systems to beam power to Earth
  - Radio-Wave WPT System
  - Light-Wave Systems
  - Photovoltaic power generation
  - Solar dynamic power generation
  - Power levels of 1 to 10 GW, beamed from geostationary orbit
- Near term Technology Flight Demonstrations
  - Model System Concept 1A: 100 kWe satellite
  - Model System Concept 1B: 10 kWe lunar system

Initial Photovoltaic / Microwave SPS GEO Sun Tower Conceptual Design

- "Sun-Tower" Design based on NASA Fresh Look Study
- Transmitter Diameter: 500 meters
- Vertical "Backbone" Length: 15.3 km (gravity gradient)
- Identical Satellite Elements: 355 segments (solar arrays)
- Autonomous Segment Ops:
  1) Solar Electric Propulsion from Low Earth Orbit
  2) System Assembly in Geostationary orbit
- Large Rectenna Receivers: Power production on Earth



Photovoltaic / Laser-Photovoltaic SPS
GEO Sun Tower-Like Concept



Full Sun Tower Portion
- **1530 modules**
- **55 km long**
- **Backbone can be eliminated**

Current Boeing Study

- **Task 1. Mission analysis for space solar power**
  - Military mission needs for supplying power to military bases and military vehicles in dangerous and remote locations, for peace, crisis and war situations, for both peak power load and base load
  - Civil government mission needs for supplying power to civil government bases and vehicles in dangerous and remote locations, on earth, in orbit, and deep space, for both peak power load and base load
  - Commercial user needs for supplying power to commercial users on the commercial power grid or in dangerous and remote locations, on earth, in orbit, and deep space, for both peak power load and base load
- **Task 2. Space solar power technology & architecture analysis**
  - Perform a literature search of key technologies
  - Assess architecture
  - Assess the environmental impact, political considerations, and identify stakeholders
  - Perform orbital analysis for constellation optimization of space power satellites at various orbital configurations
- **Task 3. Logistics analysis**
  - Analysis of transportation methods (e.g. rail gun, chemical rockets) for getting satellites into orbit (from moon or earth),
  - Conduct a mass-flow analysis, for converting X kg of extra-terrestrial matter (regolith, moon dust, asteroid material, or equivalent) to Y kg of satellite components via in-situ resource utilization (ISRU), then construction into space solar power satellites
- **Task 4. Cost analysis for space solar power**
  - Assess costs for manufacturing, transporting, operating, and servicing solar power satellites
  - Compare cost of energy conversion and distribution (kw-hour) for various existing and expected military, civil government, and commercial methods (solar power satellites, terrestrial solar, nuclear, fossil fuel)

Boeing Trade Studies: Assessment Criteria

Trade Categories	Assessment Criteria														
Raw Materials Source	Accessibility (distance and required delta v)	Resource extractability (complexity of mining and refining operations)	Resource quality (concentration and purity)	Resource availability (mass)	Resource variety (type)	Space environment									
Manufacturing and Integration Location (may be separate)	Accessibility (distance and required delta v)	Space environment	Available in space infrastructure												
Deployment Location	Accessibility (distance and required delta v)	Possibility for permanent stationary terrestrial reception	Visibility from receiving location	Distance to Earth	Potential interference with other space systems	Potential synergy/ collocation with other space systems/missions	Space environment	Duration of blackout periods	Insolation	Need for active pointing/ orientation					
Space Transportation	Launch reliability	Payload mass per launch to destination	Achievable launch rate	Transfer time to destination	Total launch cost per payload mass	Available payload volume	Payload loads and accelerations	Required infrastructure	Scaleability	Return capability	Technology maturation	Safety	Environmental impact	Propellant deman	Required power
Energy Conversion	Conversion efficiency	Power conversion capacity per mass	Reliability	Operational life	Degradation	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation							
Energy Transmission	Transmission efficiency	Power transmission capacity per mass	Transmission accuracy and interference risk	Transmission intensity and ground safety	Required ground infrastructure and area	Total life cycle cost per mass	Need for terrestrial materials	Degradation	Reliability	Operational life	Technology maturation				
Energy Storage	Storage efficiency	Energy storage capacity per mass	Energy storage and release rate per mass	Reliability	Operational life	Degradation	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation						
Electronic Components	Memory sizes	Data rates	Reliability	Required power	Total life cycle cost per mass	Operational life	Degradation	Installed mass	Need for terrestrial materials	Technology maturation					
Electronics Architecture	Redundancy	Resilience	Reliability	Required power	Total life cycle cost per mass	Operational life	Degradation	Installed mass	Technology maturation						
Comand and Control Data Links	Bandwidth	Transmission range	Reliability	Required power	Transmission security and risk of interference	Installed mass	Operational life	Degradation	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation				
Attitude and Orbit Control	Mass fraction	Need for and type and mass of reactants/ propellants	Required power	Passive stability	Reliability	Operational life	Degradation	Scaleability	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation				
Structural Concept	Mass fraction	Operational life	Reliability	Degradation	Need for terrestrial materials	Scaleability	Element size and mass	Modularity	Stability	Technology maturation					
Thermal Management	Heat rejection capability per mass	Operational life	Reliability	Degradation	Installed mass	Required power	Total life cycle cost per mass	Need for terrestrial materials	Technology maturation						
Concentrators	Mass fraction	Operational life	Reliability	Degradation	Need for terrestrial materials	Scaleability	Modularity	Shape complexity	Technology maturation						
Element Connection	Mass fraction	Operational life	Reliability	Degradation	Required power	Total life cycle cost per mass	Need for terrestrial materials	Scaleability	Stability	Technology maturation					
System Configuration	Redundancy	Resilience	Reliability	Mass fraction	Required power	Total life cycle cost per mass	Element size and mass	Scaleability	Technology maturation						
Manufacturing, Assembly and Maintenance Operations	Number of needed crew per installed power capability	Number of needed robots per installed power capability	Logistics and support requirements	Reliability	Total life cycle cost per installed power capability	Required infrastructure	Crew safety (mission risks and need for EVAs)	Number of different operational locations	Size, mass and complexity of robots	Mission duration for human crew	Technology maturation	Resilience	Deployed architecture mass		

Key	
	Potential Showstopper
	Highly Critical Decision Driver
	Critical Decision Driver
	Tiebreaker Only

Boeing Trade Studies: Ratings of Options

Trade Categories	Trade Options													
Raw Materials Source	Earth	Moon	Near Earth Objects	Phobos/ Deimos										
Manufacturing and Integration Location (may be separate)	Low Earth Orbit (LEO)	Sun Synchronous Orbit (SSO)	Medium Earth Orbit (MEO)	High Earth Orbit (HEO)	Geostationary Earth Orbit (GEO)	Molniya Earth Orbit	Earth-Moon Libration points and halo orbits	Earth-Sun Libration points and halo orbits	Lunar surface	Earth surface	Mars orbit			
Deployment Location	Low Earth Orbit (LEO)	Sun Synchronous Orbit (SSO)	Medium Earth Orbit (MEO)	High Earth Orbit (HEO)	Geostationary Earth Orbit (GEO)	Molniya Earth Orbit	Earth-Moon Libration points and halo orbits	Earth-Sun Libration points and halo orbits	Lunar surface					
Space Transportation	Launch vehicles and spacecraft with chemical propulsion (expendable and reusable)	Spacecraft with solar electric (electrostatic/ electrothermal/ electromagnetic) propulsion (in space only)	Spacecraft with solar thermal propulsion (in space only)	Solar/electric/ magnetic sails (in space only)	Tethers (mechanical/ electrodynamic) (in space/upper atmosphere only)	Electromagnetic mass drivers/rail guns and catchers	Lofstrom launch loop/space cable	Launch ring/ slingatron	External laser/ microwave propulsion	Light gas guns	Space elevator/ orbital ring	Space fountain/ orbital tower	Spacecraft with nuclear fission propulsion (thermal/electric/ pulsed detonation)	Spacecraft with fusion/ antimatter propulsion
Energy Conversion	Photovoltaic	Solar dynamic/ thermodynamic/ magnetohydrodynamic	Thermionic/ thermoelectric	Solar pumped laser/maser	Signal processing solutions	Nanofabricated rectenna	Optical rectenna	Rapidly ionizing plasma	Optical resonators	Shocked photonic crystals	None (reflection only)			
Energy Transmission	Laser (visible/ Infrared)	Microwave/maser	Physical transfer of energy storage media	Cable (in GEO only)	Focused reflection	Relay satellites/ mirrors								
Energy Storage	Supercapacitors	Superconducting magnetic	Reversible fuel cells	Batteries	Thermal storage/phase change material	High energy density matter	Flywheels	None (real time power transmission only)						
Electronic Components	Standard space qualified	Nanotechnology	Radiofrequency connections	Commercial off the shelf	Superconductors	Optical								
Electronics Architecture	Distributed	Centralized												
Comand and Control Data Links	Radiofrequency	Laser (visible/Infrared)												
Attitude and Orbit Control	Reaction control systems	Electromagnetic torque coils/rods	Electromagnetic tethers	Permanent magnets	Gyros/momentum wheels	Radiometer spin/solar sails	Gravity gradient	Spin stabilization						
Structural Concept	Solid members	Rigidized inflatables	Tethers											
Thermal Management	Passive cooling	Active cooling	None											
Concentrators	Reflective	Diffractive	Refractive	None										
Element Connection	Rigid attachements	Articulated joints	Free flying elements											
System Configuration	Functionally integrated identical modules	Monolithic elements with separate functions	Distributed elements with separate functions											
Manufacturing, Assembly and Maintenance Operations	Purely Human	Human/robotic cooperation	Human tended robotic	Purely robotic with local human supervision	Purely robotic with remote human supervision	Self replicating intelligent autonomous robots								

Key	
	Baseline (Most Preferred) Option
	Highly Preferred Option
	Less Preferred Option
	Least Likely Option

Each trade will be assessed in terms of performance and cost

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Initial focus is on major drivers of system design and cost

Key	
	Baseline (Most Preferred) Option
	Highly Preferred Option
	Less Preferred Option
	Least Likely Option

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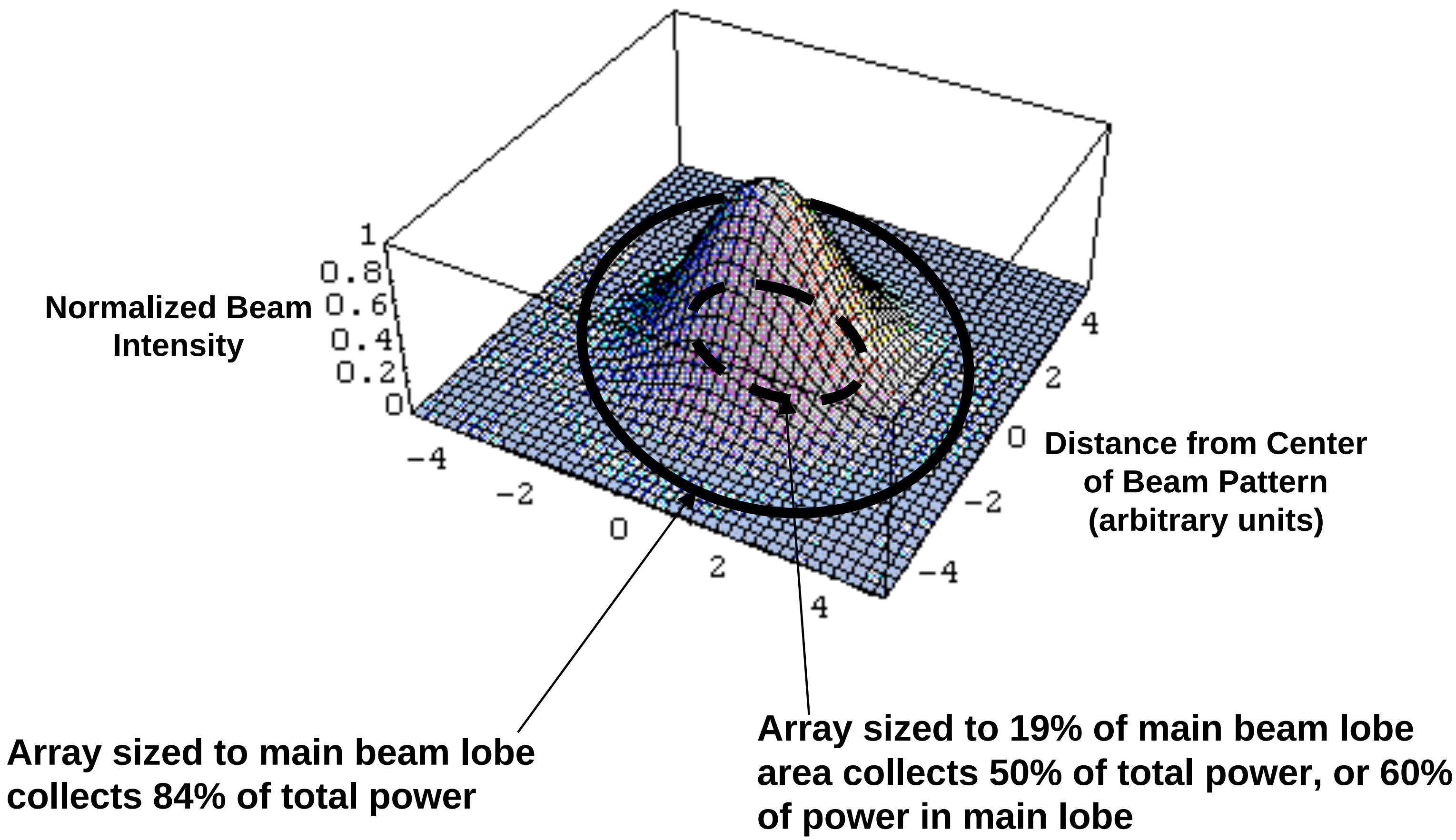
Sizing of Receiver Array

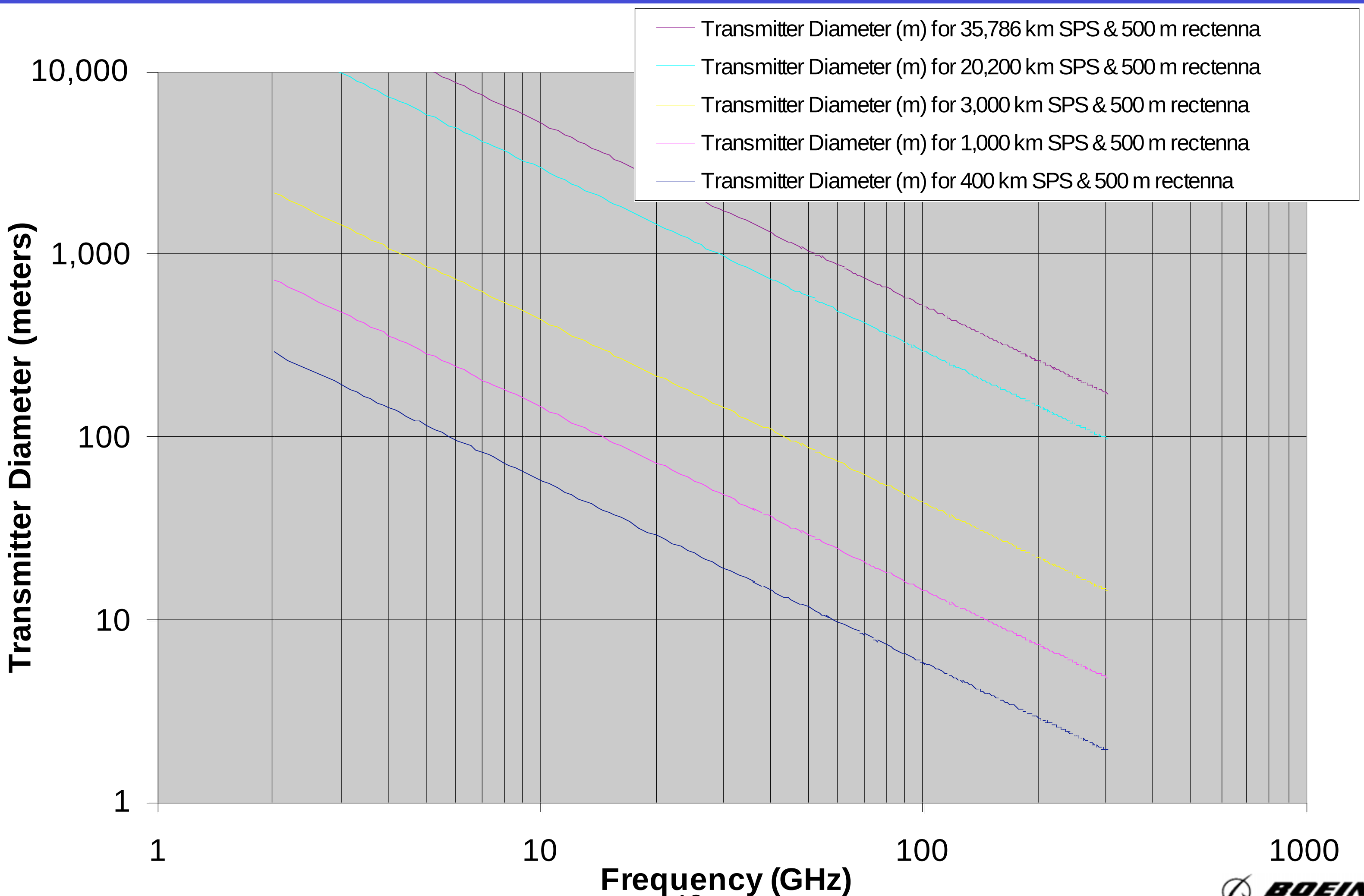


Near-Term Market: Military Bases

- Much of the cost in lives and dollars of operating a military base in a war environment is due to the delivery of fuel
- Cost of delivery of gasoline under such circumstances is about \$100/gallon, which contains 130 megajoules of energy = 36 kWh
- At this rate, 40 remote military bases (each using 5 MW) will require 40 bases x 5 MW/base x 24 hours/day x 30 days/month = 144,000 MWh/month
- This is equivalent to 4,000,000 gallons of fuel per month or \$400 million per month for fuel.
  - Conversion from thermal to electrical energy not accounted for. Actual fuel usage will be higher.
- These bases, using a total of 200 MW could instead be supplied by just 20% of the power beamed from a single 1 GW power satellite
- Graceful growth toward this market may be achievable by considering a constellation of smaller (5 to 10 MW) satellites.

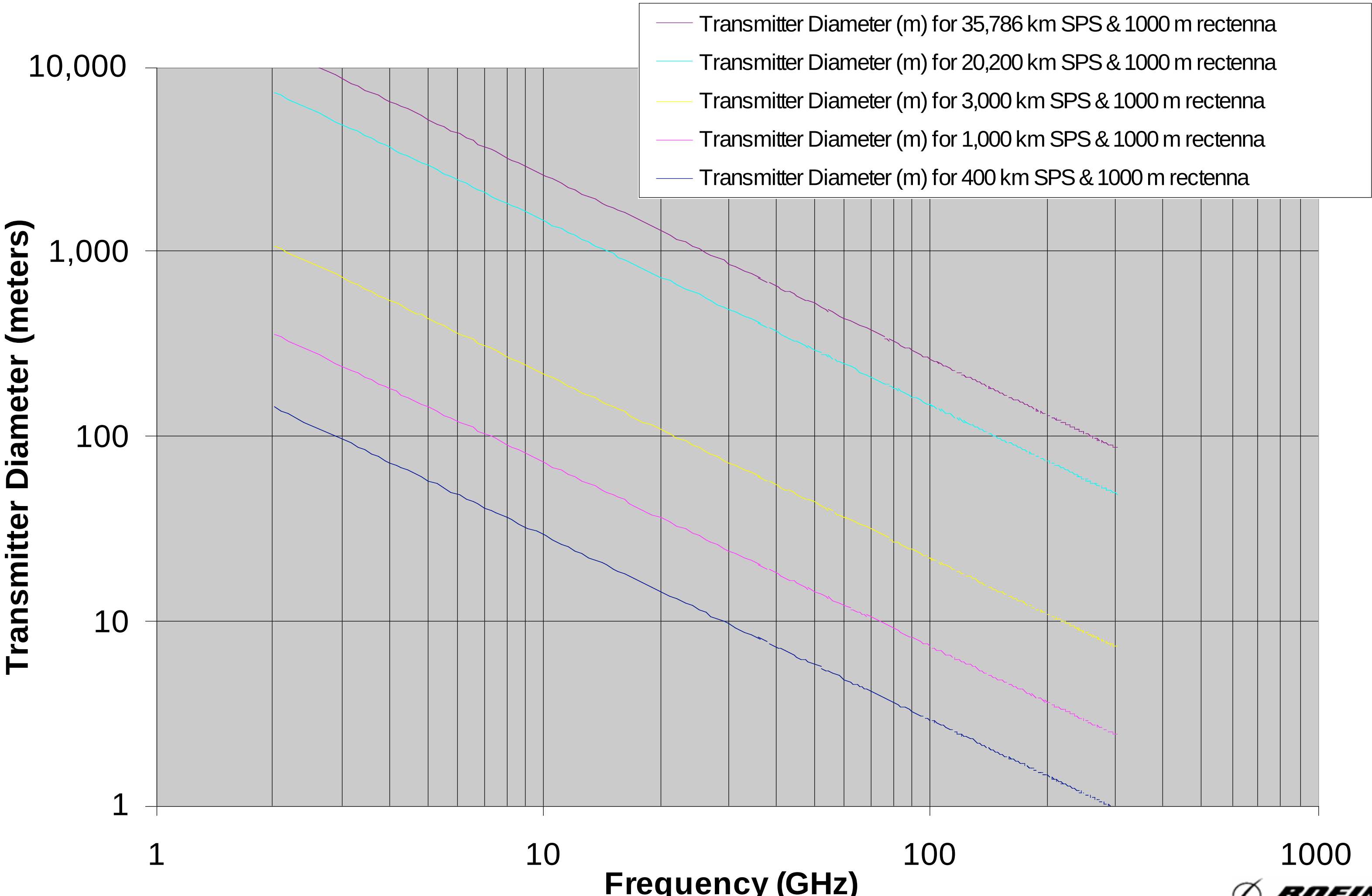
Near-Term Market: Military Bases

Case 1: 500-meter rectenna – can receive up to 10 MW at power densities comparable to earlier studies (~22 mW/cm² peak)



Near-Term Market: Military Bases

Case 2: 1000-meter rectenna – can receive up to 40 MW at power densities comparable to earlier studies (~22 mW/cm² peak)



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Orbit Trade Study: Altitude (1 of 2)

- Low Earth Orbit (LEO)
  - Pros:
    - Low delta-V, so lower launch costs
    - Less beam divergence, therefore smaller overall system size, leading to lower cost to first power and ease of integration into near-term niche markets
    - Graceful growth and degradation
  - Cons:
    - Satellite is in view of a given rectenna for only a few minutes per orbit, so many satellites and rectennas would be necessary to maximize power transmission duty cycle and minimize storage
    - Beam must be continuously steered, leading to steering losses and sweeping out large exclusion zones
    - Prone to greater drag and space debris
    - In darkness much of the time, further lowering duty cycle and increasing cost per installed watt
      - A LEO sun-synchronous orbit may be in sunlight continuously, but may not pass over desired sites often

Orbit Trade Study: Altitude (2 of 2)

- High Earth Orbit, particularly GEO
  - Pros:
    - Satellite has long dwell time over rectenna (continuous in GEO), so little or no beam steering is necessary
    - Minimal beam steering losses
    - In almost continuous sunlight
    - Exclusion zone around beam is large, but fixed
  - Cons:
    - High delta-V, so high launch costs
    - High beam divergence, therefore:
      - Large antenna size
      - Large overall system size, leading to higher cost to first power, complex assembly, and challenging integration into existing markets
    - Must transmit beam through lower orbits
- Middle Earth Orbit (MEO)
  - Most pro and con characteristics are intermediate between LEO and GEO, however …
  - Taking full advantage of MEO altitude may involve placing it in higher inclination orbits. This would have the advantage of placing the satellite over areas where it is needed much of the time, and may keep it in continuous sunlight much of the year. However, the delta-V to launch to a highly inclined MEO orbit may actually be greater than that for GEO.

Orbit Trade Study: Inclination

- Low Inclination
  - Pros:
    - Natural inclination for GEO orbits
    - Low delta-V
  - Cons:
    - LEO satellites would be in darkness much of the time
    - LEO satellites may not be visible at middle and high latitudes
- High Inclination
  - Pros:
    - Ground track may cover inhabited areas, so that greater use can be attained by LEO and MEO satellites
    - Sun-synchronous orbits may be achievable for LEO orbits, keeping them in sunlight much of the time if orbit is over terminator
  - Cons:
    - Higher delta-v for a given altitude
    - If sun-synchronous, the near-polar inclination may limit beaming opportunities

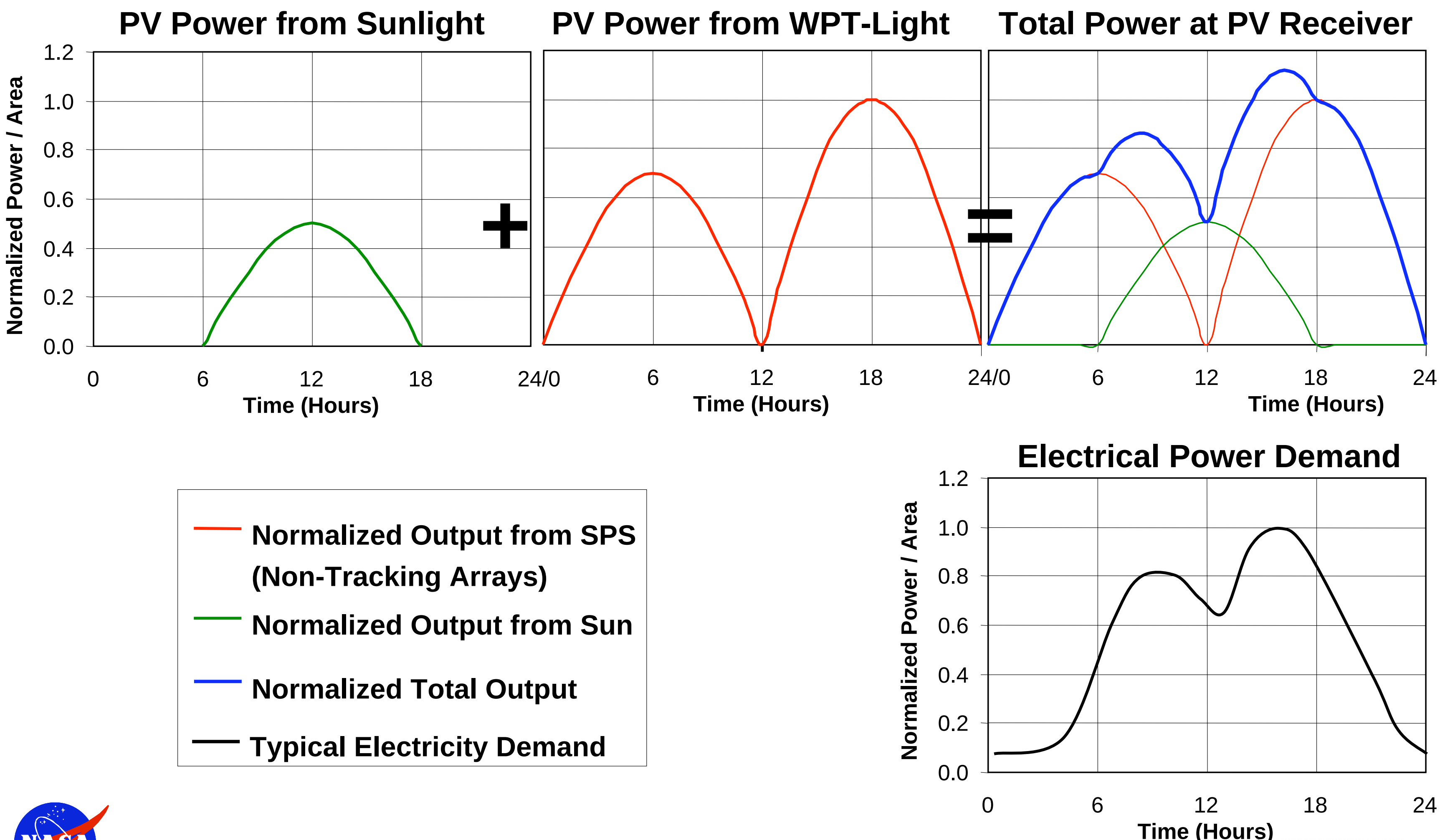
Orbit Trade Study: Eccentricity

- Low Eccentricity (circular)
  - Pros:
    - Natural for GEO orbits, and default for most satellite missions
- High Eccentricity (elliptical; Molniya-like)
  - Pros:
    - Can deliver large amounts of power to high latitudes by being in view of rectenna and sun for much of its orbit (i.e., long "hang time" over customer) – same rationale as Molniya
      - Lower delta-V than for low eccentricity orbits at same apogee
      - Critical inclination of 63.4 degrees or 116.6 degrees is suitable for high latitudes
    - For smaller amounts of power, may be able to deliver to niche customers (e.g., military bases) in a store- (around apogee) and-dump (around perigee) mode
  - Cons:
    - Limited to critical inclinations of 63.4 degrees or 116.6 degrees to keep perigee from precessing (unless innovative constellation design takes advantage of this precession)
    - Very short dwell times over rectenna in store-and-dump mode
    - Beam steering is necessary
    - Beam spot size and intensity at rectenna is continuously changing
    - Satellite must be designed for a variety of space environments

Synergy Between Sunlight and Laser-PV WPT for Terrestrial Photo-Voltaic Power Production

- Large photo-voltaic (PV) power plants in Earth's major deserts (Mojave, Sahara, Gobi, etc.) receive & convert light from 2 sources:
  1) Directly from the Sun, and
  2) Via WPT from SSP systems
- Laser light is transmitted and converted more efficiently than sun-light
  - Wavelength is selected for good atmospheric transmissivity
  - Efficient Light Emitting Diode wavelengths match common PV band-gaps
- Gravity gradient-stabilized SPSs are in peak insolation at ~6 AM and ~6 PM, with shadowing or cosine loss at mid-day and midnight
  - Heavy, complex gimbaled arrays add little extra power at these times
  - Both sides of rigid (not gimbaled) solar arrays can be light-sensitive
    - Back-side produces less power due to occlusion by wires
    - Translucent substrate (e.g., Kapton) also reduces back-side power levels
  - Even gimbaled arrays suffer a loss of power around noon and midnight
- The combination of ambient sunlight plus laser illumination combines, at the terrestrial PV array, to match the daily electricity demand pattern

Sunlight + Laser-PV WPT = ~ Power Requirement
Photo-Voltaic (PV) Power Station Receives Both



WPT Wavelength Trade for SSP

ATTRIBUTE	WPT Using Radio Waves	WPT Using Light Waves
Aperture Size	Large, so system must be large	Small; allows flexible system design
Interference	Radio Frequency Interference	None, except perhaps astronomy
Attenuation	Penetrates clouds and light rain	Stopped by clouds (need desert area)
Legal Issues	FCC, NTIA, ITU	ABM treaty, if power density high
Infrastructure	Rectenna useful for SSP only	PV array for both WPT & solar power
Dual Use	Crops?; communications?	PV arrays on rooftops; "solar"-sails?
Perception	Public fears of "cooking"	Government fears of "weapons"
Safety	Safe (must keep aircraft out of beam)	Safe (WPT light intensity < sunlight)
Efficiency (space)	High	Improving
Efficiency (ground)	High	Improving
Traceability	Heritage to communications & radar	MSC-1 and MSC-2 predecessors
Power Mgmt & Dist	Heavy, due to centralized WPT	Lightweight; WPT can be distributed

Area of Significant Concern (pink)
Intermediate Area (yellow)
Area of Significant Benefit (green)

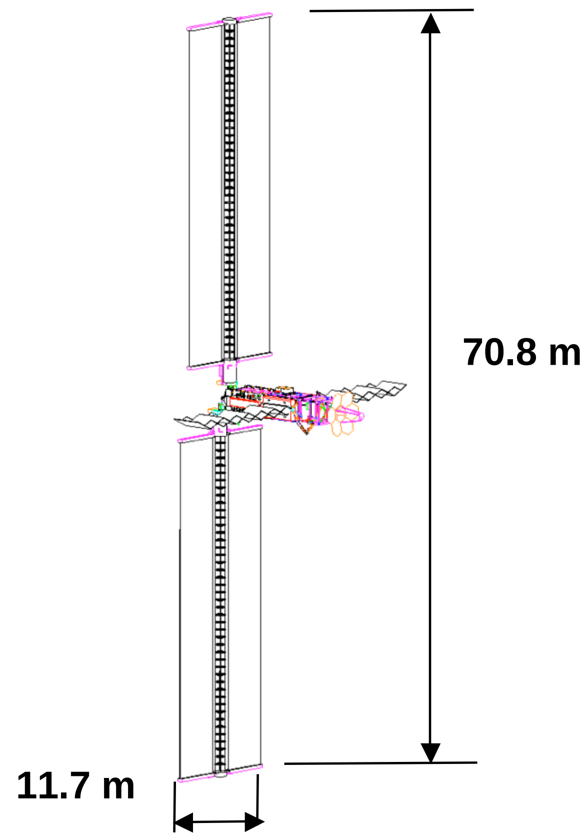
Power Generation Trade for SSP

ATTRIBUTE	PHOTOVOLTAIC	SOLAR DYNAMIC
Solar Collector Area	Moderately high, but improving	*Low*
Radiation Tolerance	Degrades	*Excellent*
Specific Power	Moderate	Low, but should be high in far term
Efficiency	*~25% SOA with rainbow cells*	*Currently 29%; expect 35% in far term*
Heat Tolerance	Loses efficiency as Temp. rises	*Excellent; requires heat*
Moving Parts	*None*	Rotating machinery, fluids
Modular Construction	*Yes*	Less so
Experience in Space Environment	*Extensive use on satellites*	Vacuum chamber only

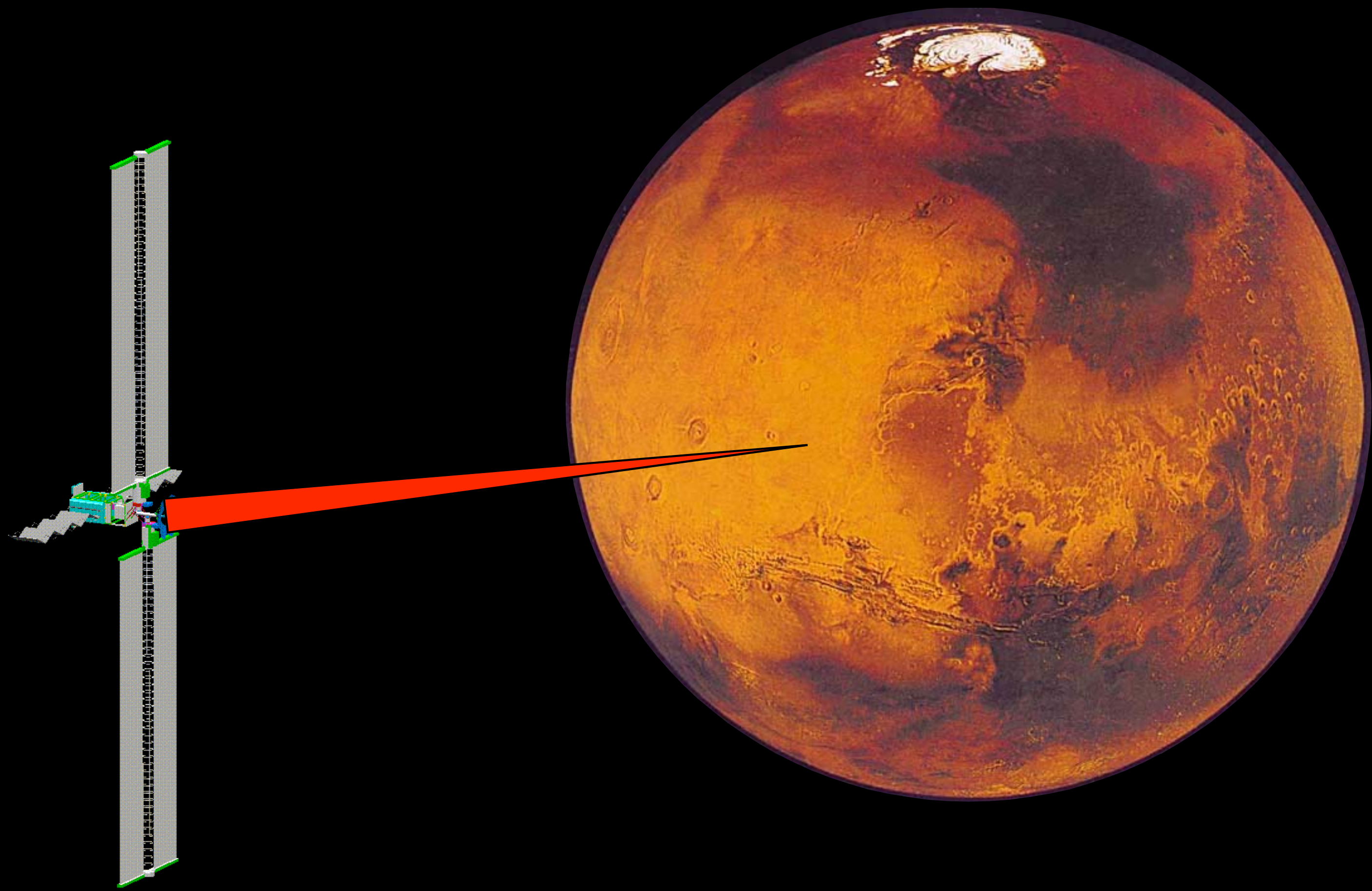
Area of Significant Concern
Intermediate Area
Area of Significant Benefit

MSC-1A: Near Term Demonstration
100 kWe Power Plug Satellite

- Power System derived from existing ISS IEA (Integrated Energy Assembly)
  - IEA is successfully deployed in orbit now
  - IEA includes energy storage (batteries)
  - Current ISS array pair produces 61.5 kWe
  - Advanced PV cells can double IEA power
    - ~120 kWe with derivative array
- MSC-1 demonstrates solar-powered WPT
  - Efficient power generation
    - Light Emitting Diodes (LEDs) achieve >30% conversion efficiency
    - ~36 kW transmitted in light beam
  - Effective heat dissipation via IEA radiators
  - Accurate pointing of beam via reflector

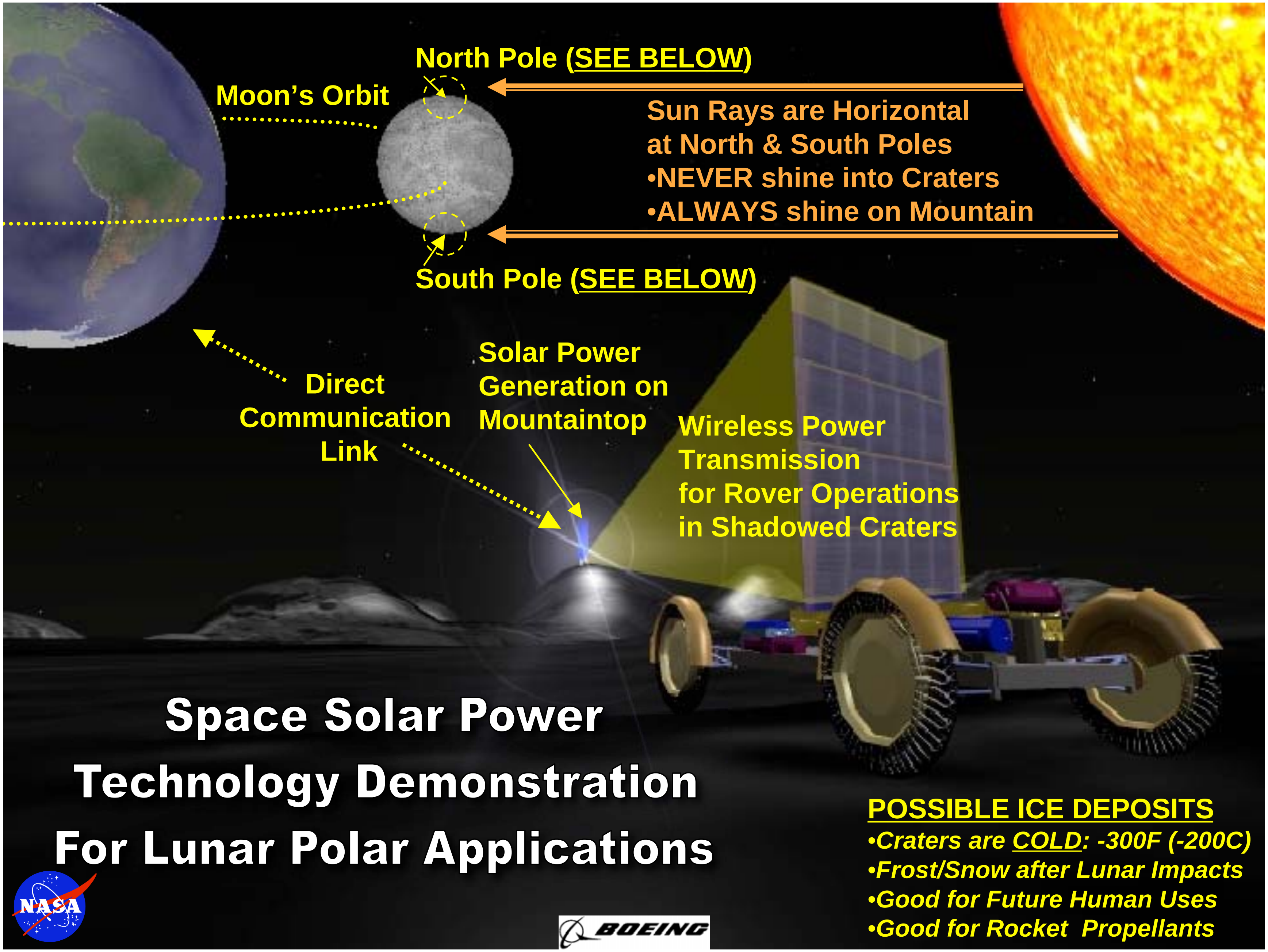


MSC-1A: Lunar and Mars Power (LAMP) Application
Laser WPT to Photovoltaics on the moon or Mars



MSC 1B: Lunar Polar Science Applications

- Technology for Laser-Photo-Voltaic Wireless Power Transmission (Laser-PV WPT) was assessed for lunar polar applications by Boeing and NASA Marshall Space Flight Center
- A lunar polar mission could demonstrate and validate Laser-PV WPT and other SSP technologies, while enabling access to cold, permanently shadowed craters that are believed to contain ice
  - Craters may hold frozen water and other volatiles deposited over billions of years, recording prior impact events on the moon (& Earth)
  - A photo-voltaic-powered rover could use sunlight, when available, and laser light, when required, to explore a large area of polar terrain
- The National Research Council recently found that a mission to the moon's South Pole-Aitkin Basin should be a high priority for Space Science
- See paper **IAC-02-r4.04, Space Solar Power Technology Demonstration for Lunar Polar Applications,** for further details



North Pole (SEE BELOW)
Moon's Orbit
Sun Rays are Horizontal
at North & South Poles
•NEVER shine into Craters
•ALWAYS shine on Mountain
South Pole (SEE BELOW)
Direct
Communication
Link
Solar Power
Generation on
Mountaintop
Wireless Power
Transmission
for Rover Operations
in Shadowed Craters
Space Solar Power
Technology Demonstration
For Lunar Polar Applications
POSSIBLE ICE DEPOSITS
•Craters are COLD: -300F (-200C)
•Frost/Snow after Lunar Impacts
•Good for Future Human Uses
•Good for Rocket Propellants
NASA
BOEING

Summary

- Farther-term microwave WPT options are efficient, and can beam power through clouds / light rain, but require large sizes for long distance WPT and a specialized receiver (“rectenna”).
- Nearer-term Laser-Photovoltaic WPT options are less efficient, but allow synergistic use of the same photovoltaic receiver for both terrestrial solar power and SSP.
- Boeing is currently investigating near-term military, civil government, and commercial markets for SSP.
- Technology flight demonstrations can enable advanced space science and exploration in the near term.
  - “Power Plug” or “LAMP” spacecraft and Lunar Polar Solar Power outpost advance technology for far-term commercial SSP systems, while providing significant value for near-term applications.

Acronyms

- ABM = Antiballistic Missile
- FCC = Federal Communications Commission
- GEO = Geostationary Earth Orbit
- IEA = Integrated Energy Assembly
- ISS = International Space Station
- ITU = International Telecommunications Union
- km = kilometers
- kWe = kilowatt electric
- LAMP = Lunar and Mars Power
- LED = Light Emitting Diode
- LEO = Low Earth Orbit
- m = meters
- MEO = Middle Earth Orbit
- MSC = Model System Concept
- NTIA = National Telecommunications and Information Administration
- PMAD = Power Management and Distribution
- PV = Photovoltaic
- Rectenna = Rectifying Antenna
- SPS = Solar Power Satellite
- SSP = Space Solar Power
- WPT = Wireless Power Transmission