

Wireless Power Transmission Options for Space Solar Power

**Seth Potter (1), Mark Henley (1), Dean Davis (1), Andrew Born (1),
Joe Howell (2), and John Mankins (3)**

**(1) The Boeing Company, (2) NASA Marshall Space Flight Center,
(3) formerly NASA HQ, currently Artemis Innovation Management Solutions LLC**

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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



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)



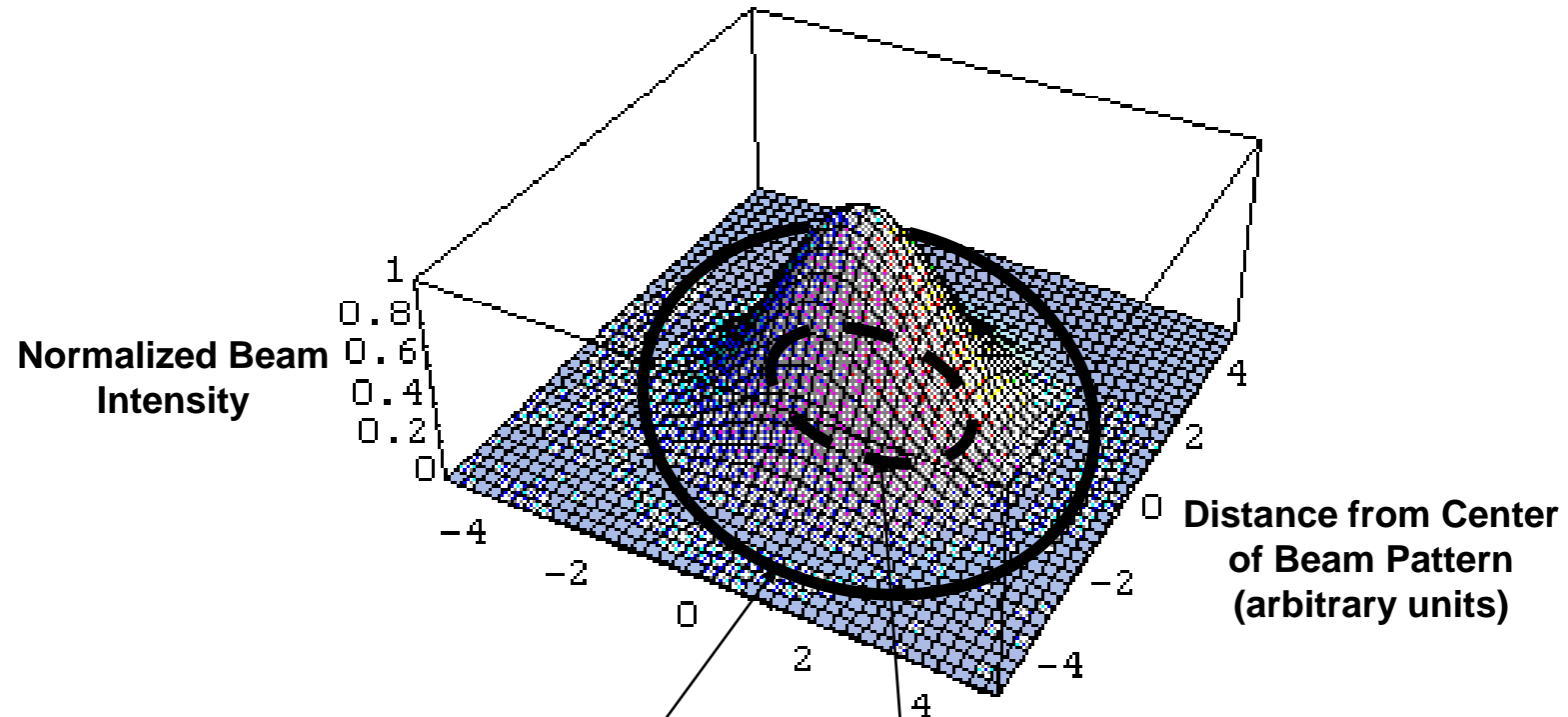
Boeing Trade Studies in Progress

Trades Categories					
	Orbit	Satellite structure	Transmission	Ground receiver	Manufacturing
Trades	Orbital altitude	Method of power generation (photovoltaic vs solar dynamic)	Laser vs microwave	Size of rectennas/receivers on earth	Transportation methods
	Eccentricity of orbit	Diameter of Transmitter	Peak beam intensity	Number of rectennas/receivers on earth	Mass-flow techniques for ISRU
	Inclination of orbit	Geometry; e.g., length of vertical "backbone" or aspect ratio of panel	Beam width	Location of receiving stations	How satellite will be assembled
	Stationkeeping details	Power levels for operational & tech flight demo satellites	Beam pattern taper		Mass-flow techniques for ISRU
	Transportation methods	Ratio of solar collector area to transmitting antenna area			
		Number of solar arrays or solar dynamic generators on satellite			
		Photovoltaic structure details (how deployed in orbit, type, size, etc)			
		Avionics details			
		Where should stationkeeping drive go? How many drives?			

Each trade will be assessed in terms of performance and cost



Sizing of Receiver PV Array



PV array sized to main beam lobe collects 84% of total power

PV array sized to 19% of main beam lobe area collects 50% of total power, or 60% of power in main lobe



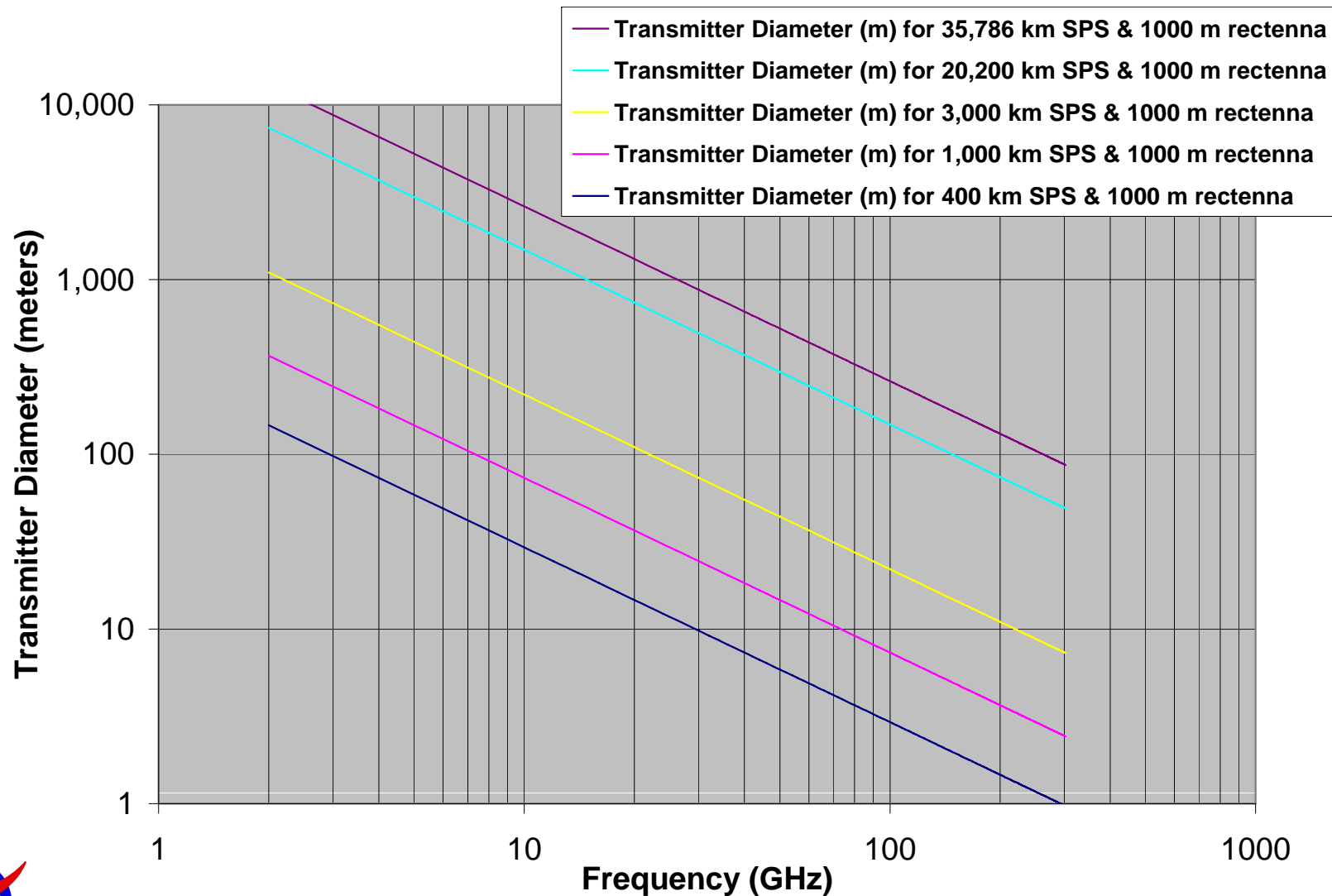
Near-Term Market: Military Bases

- 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 $40 \text{ bases} \times 5 \text{ MW/base} \times 24 \text{ hours/day} \times 30 \text{ days/month} = 144,000 \text{ MWh/month}$
- 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

Need: 5-10 MW per base, delivered to a rectenna 1000 m in diameter or less, within the base



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



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, time of overflight would be required to be near sunrise and sunset each orbit
 - This could constrain choice of altitudes if repeating ground track is desired

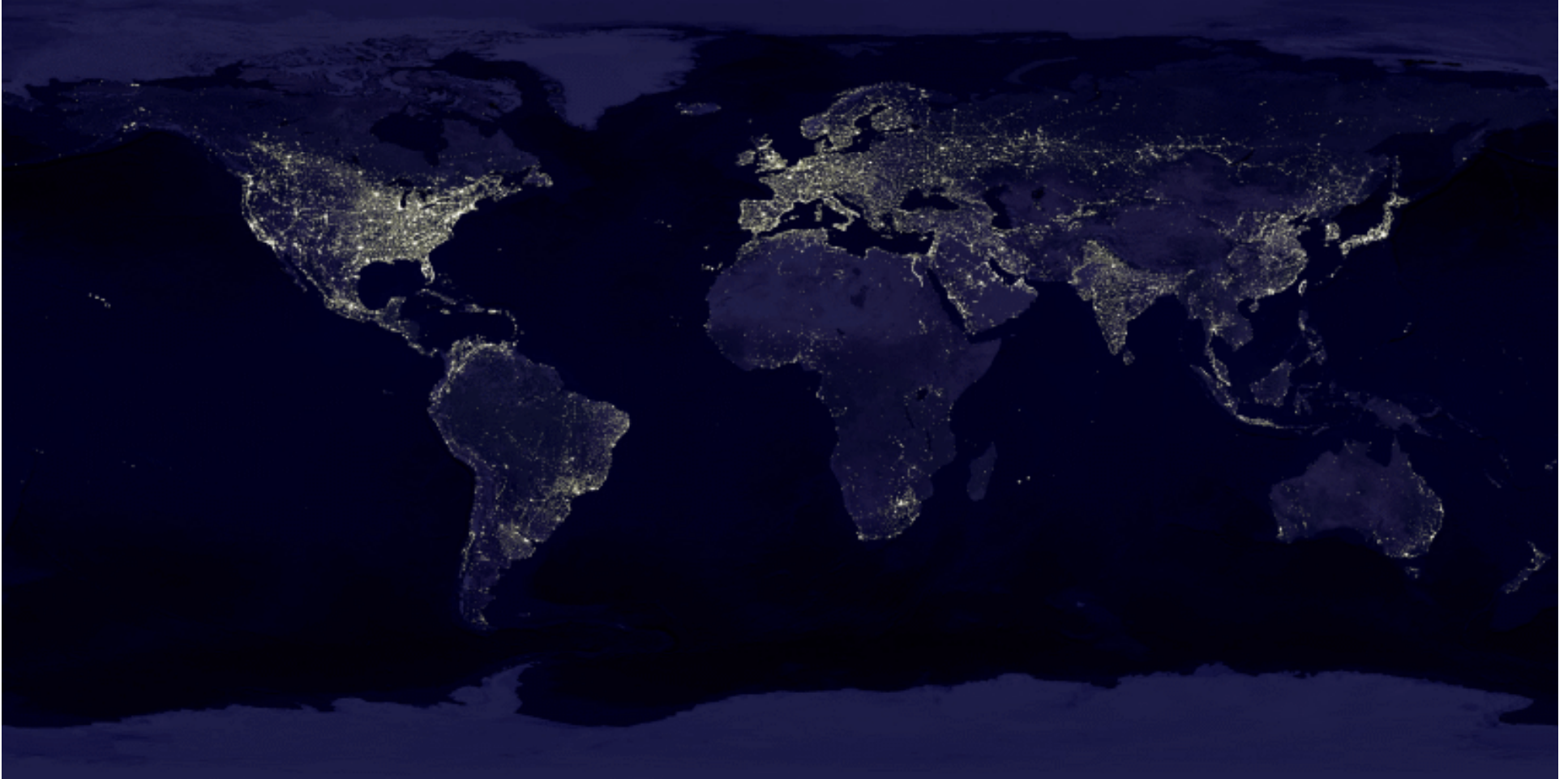


Orbit Trade Study: Eccentricity

- 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



Global Power Consumption

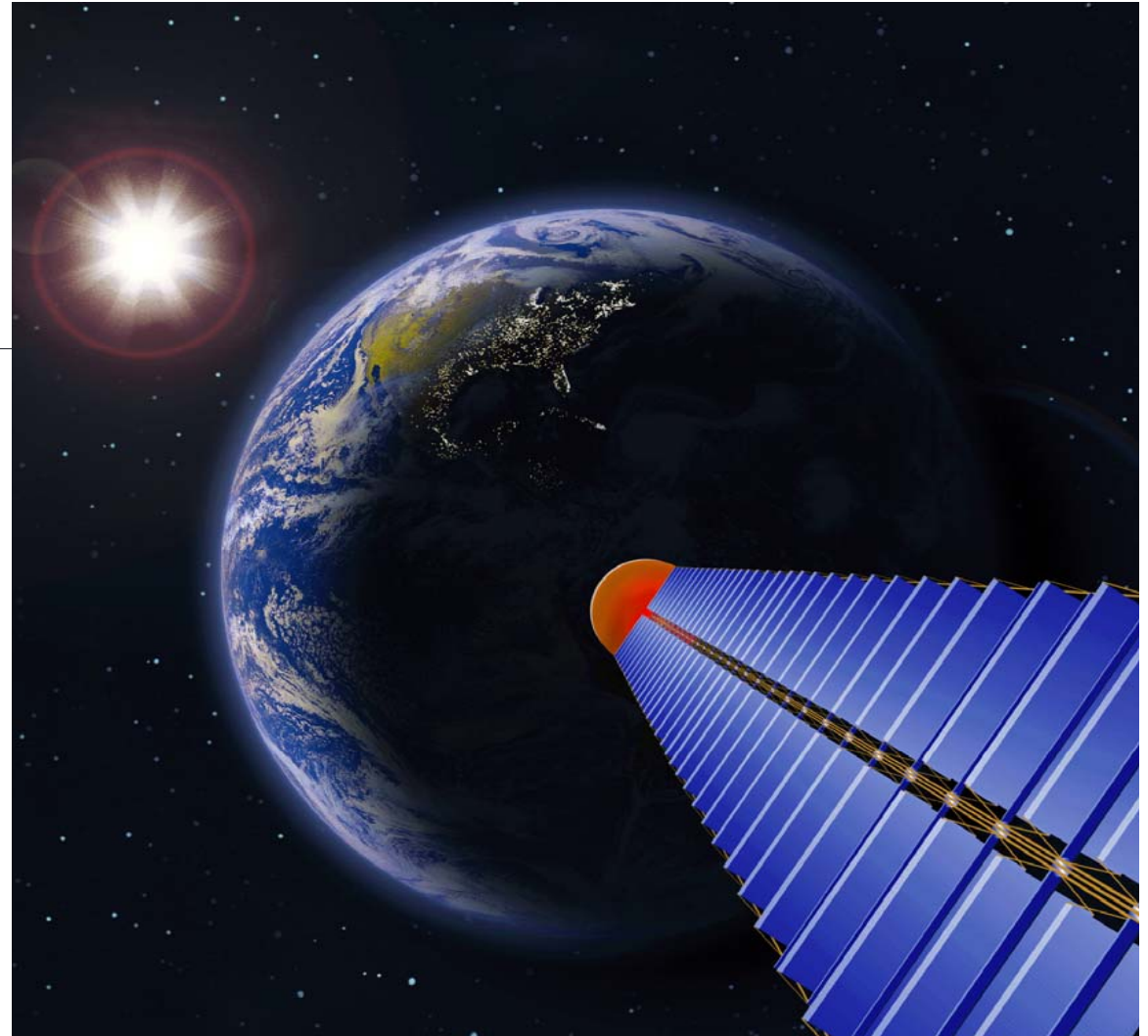


Remote Sensing of Current Global Power Consumption:
A Composite Satellite Photograph of the Earth at Night



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

Solar Panel Segment

Dimensions: 260 m x 36 m

Lasers and Optics

PMAD

8 Ion Thrusters

Avionics

Deployable Radiator

Full Sun Tower Portion

- 1530 modules
- 55 km long
- Backbone can be eliminated

Multiple beams

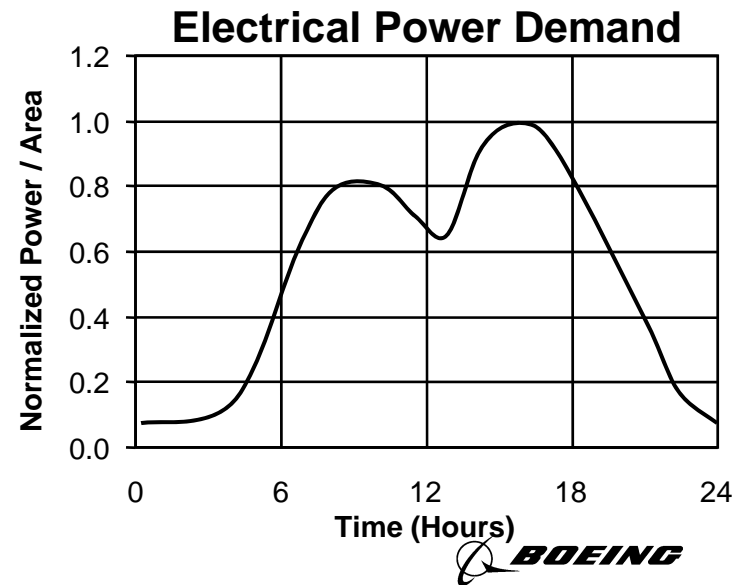
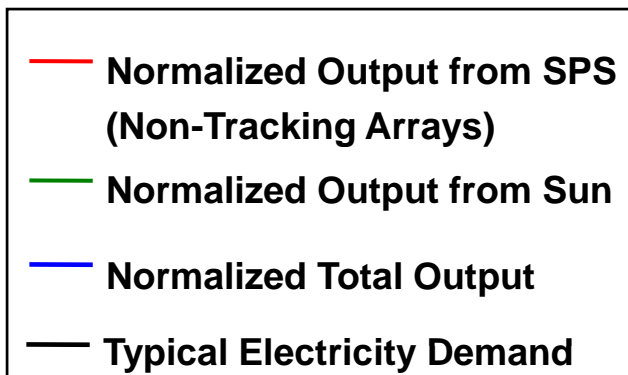
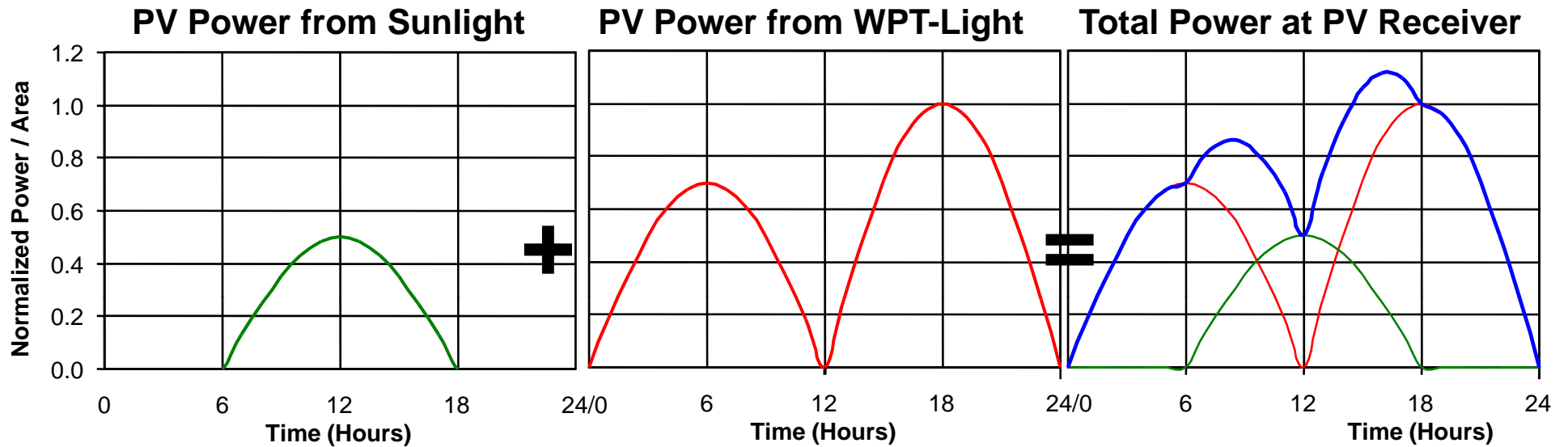


Synergy Between Sunlight and Laser-PV WPT for Terrestrial Photo-Voltaic Power Production

- 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

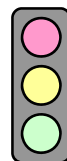


Sunlight + Laser-PV WPT = ~ Power Requirement Photo-Voltaic (PV) Power Station Receives Both



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




Intermediate Area

Area of Significant Benefit



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

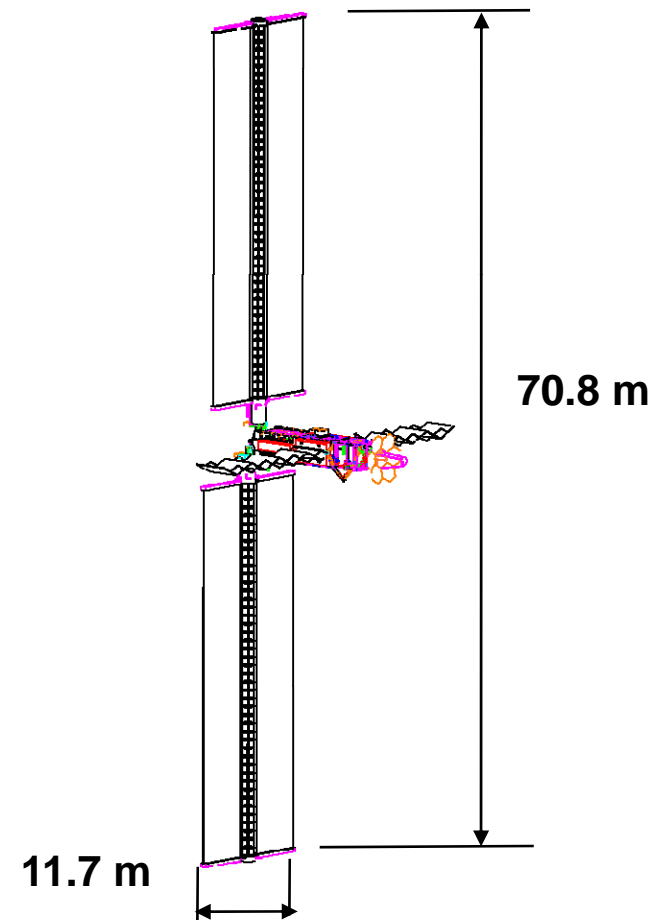
	Area of Significant Concern
	Intermediate Area
	Area of Significant Benefit



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

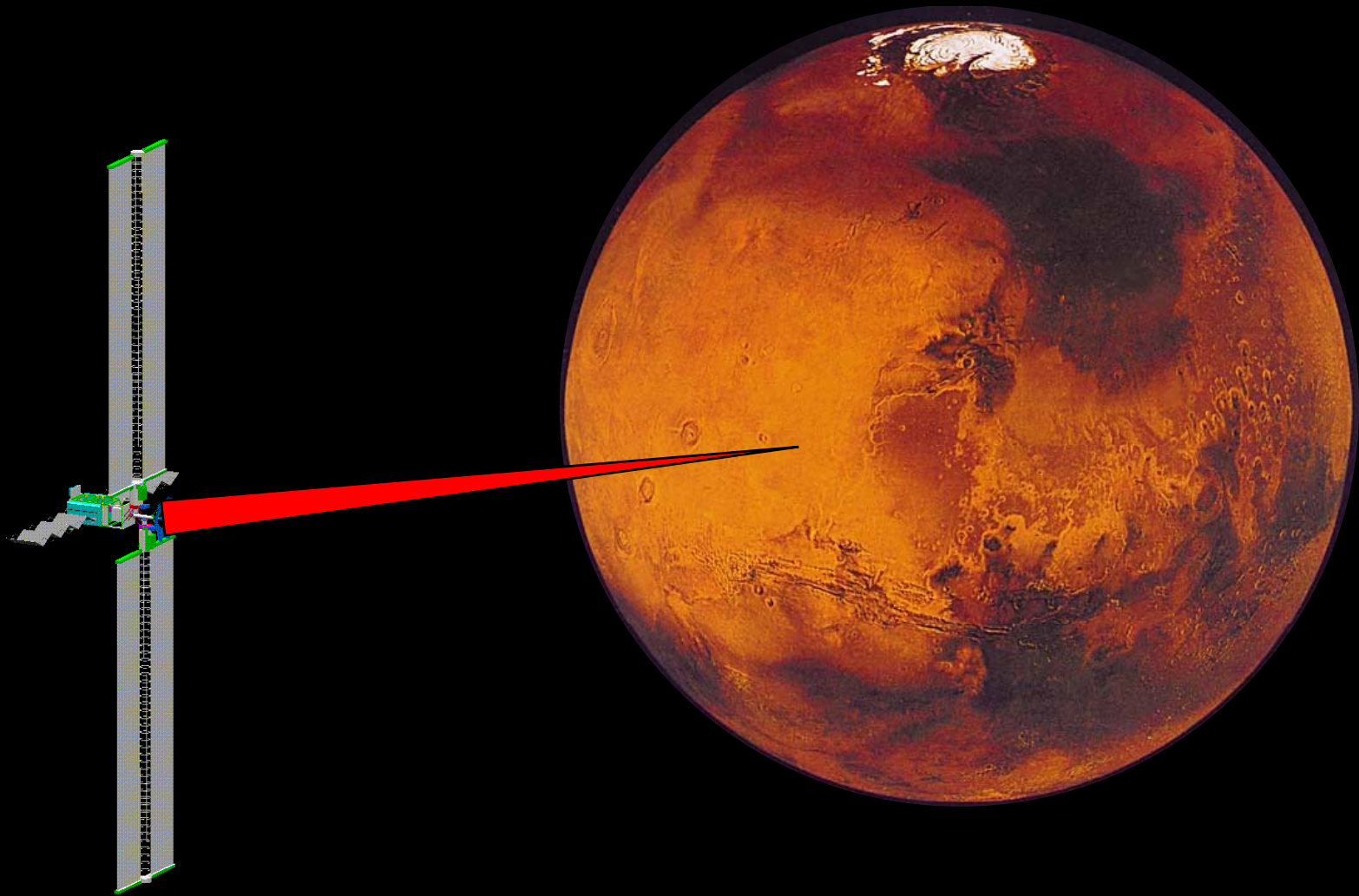


ISS with IEA Solar Panels Fully Deployed

Current flight experience with large IEA reduces risk for near-term derivative applications



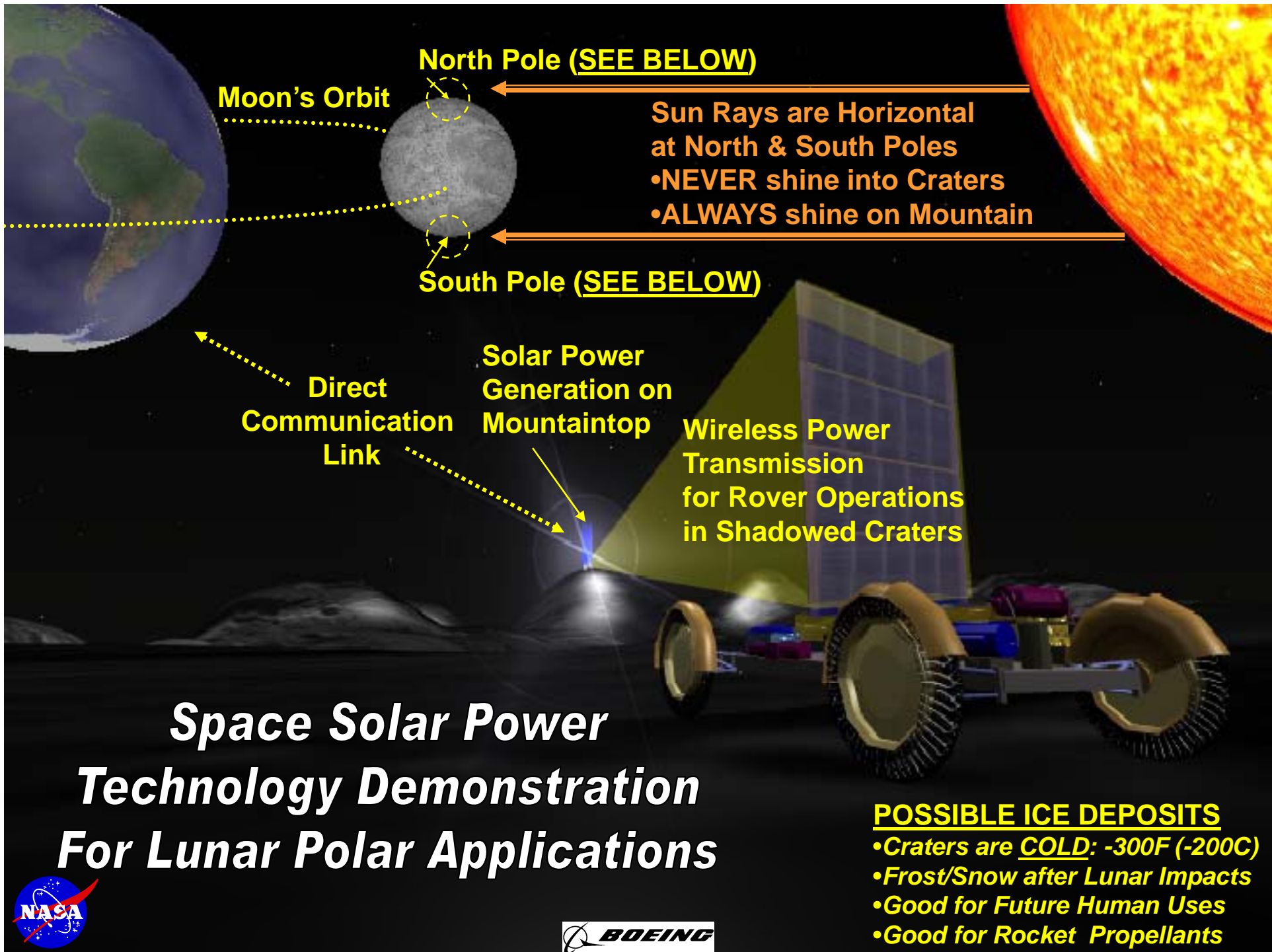
MSC-1A: Lunar and Mars Power (LAMP) Application Laser WPT to Photovoltaics on the moon or Mars



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



Summary

- Farther-term micro-wave 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

