

Wireless Power Transmission Options for Space Solar Power

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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 15 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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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)



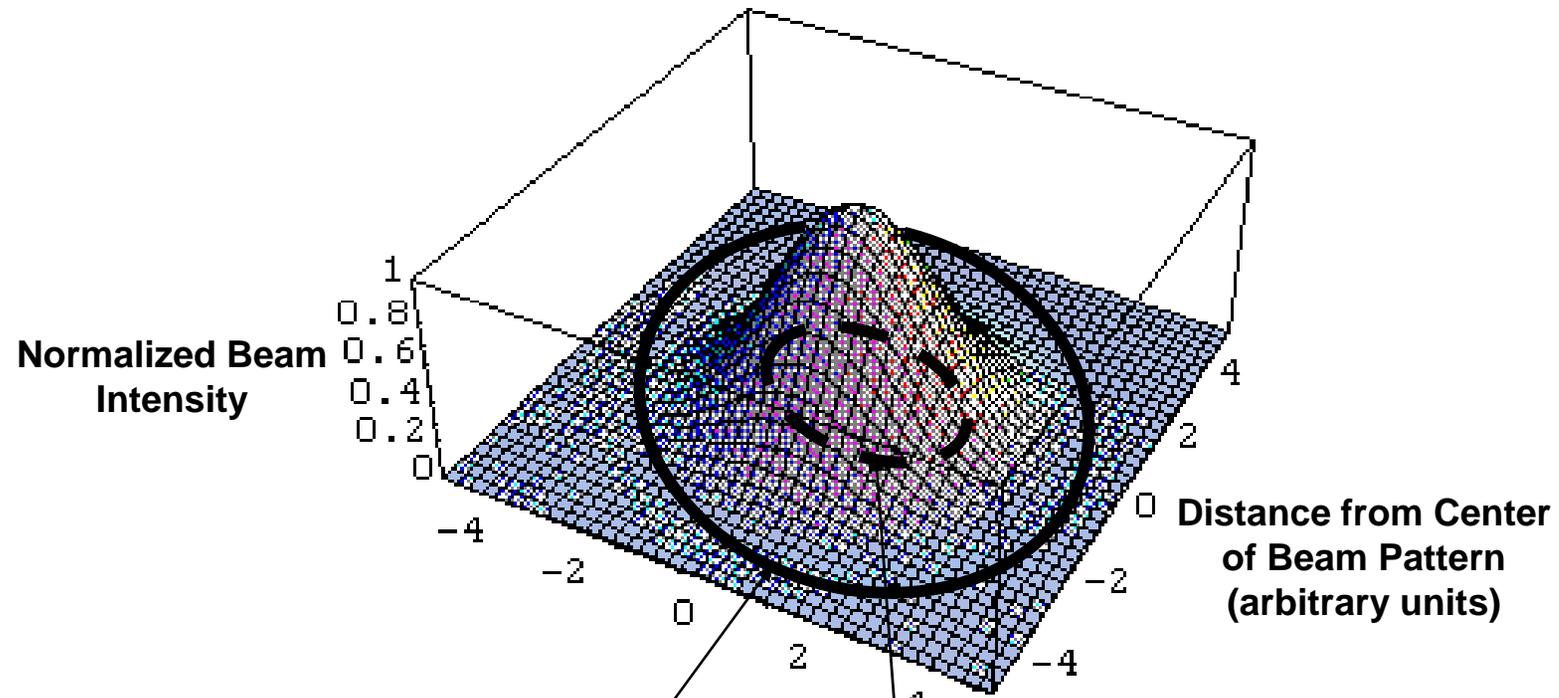
Boeing Trade Studies in Progress

| 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



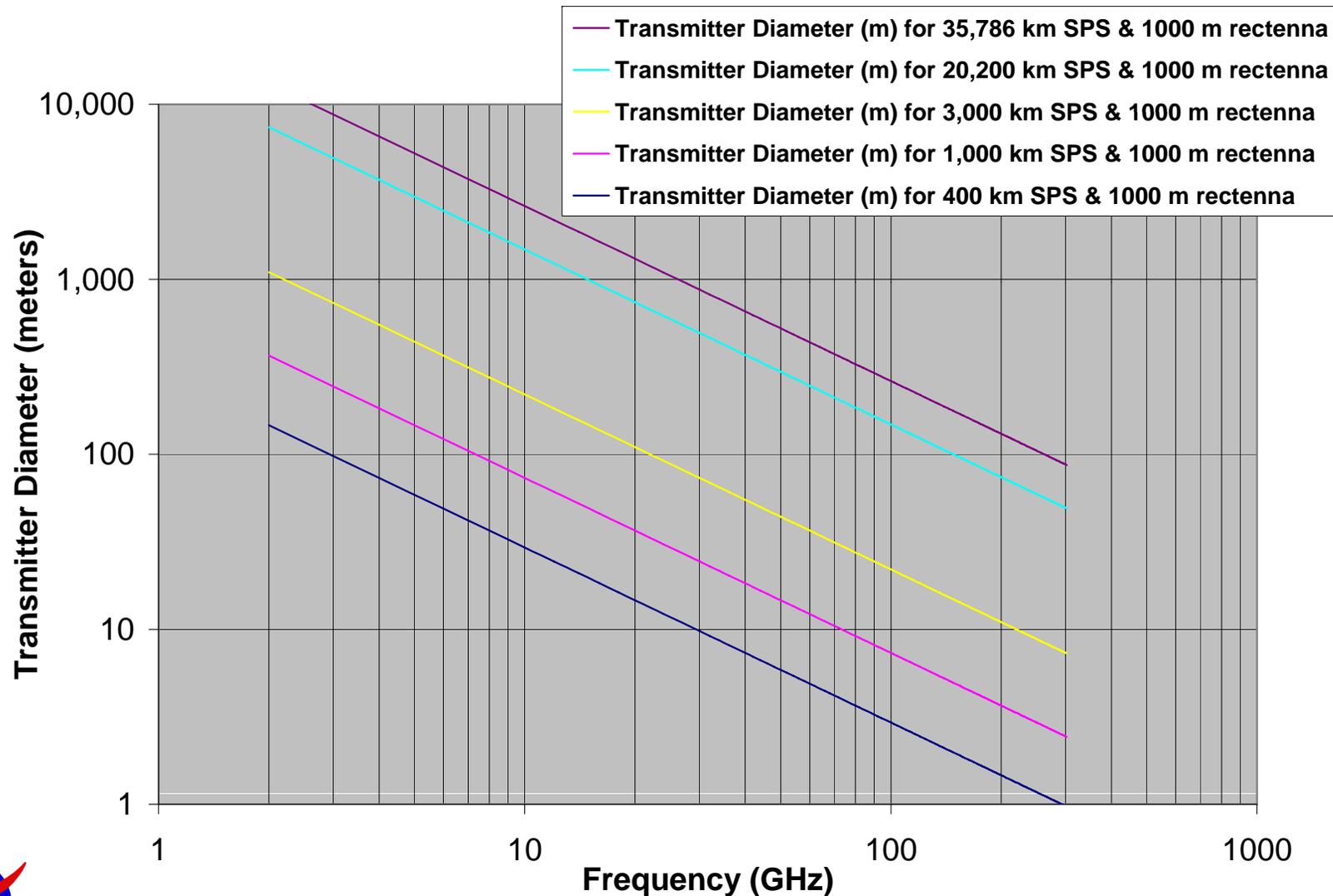
Near-Term Market: Military Bases

- 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

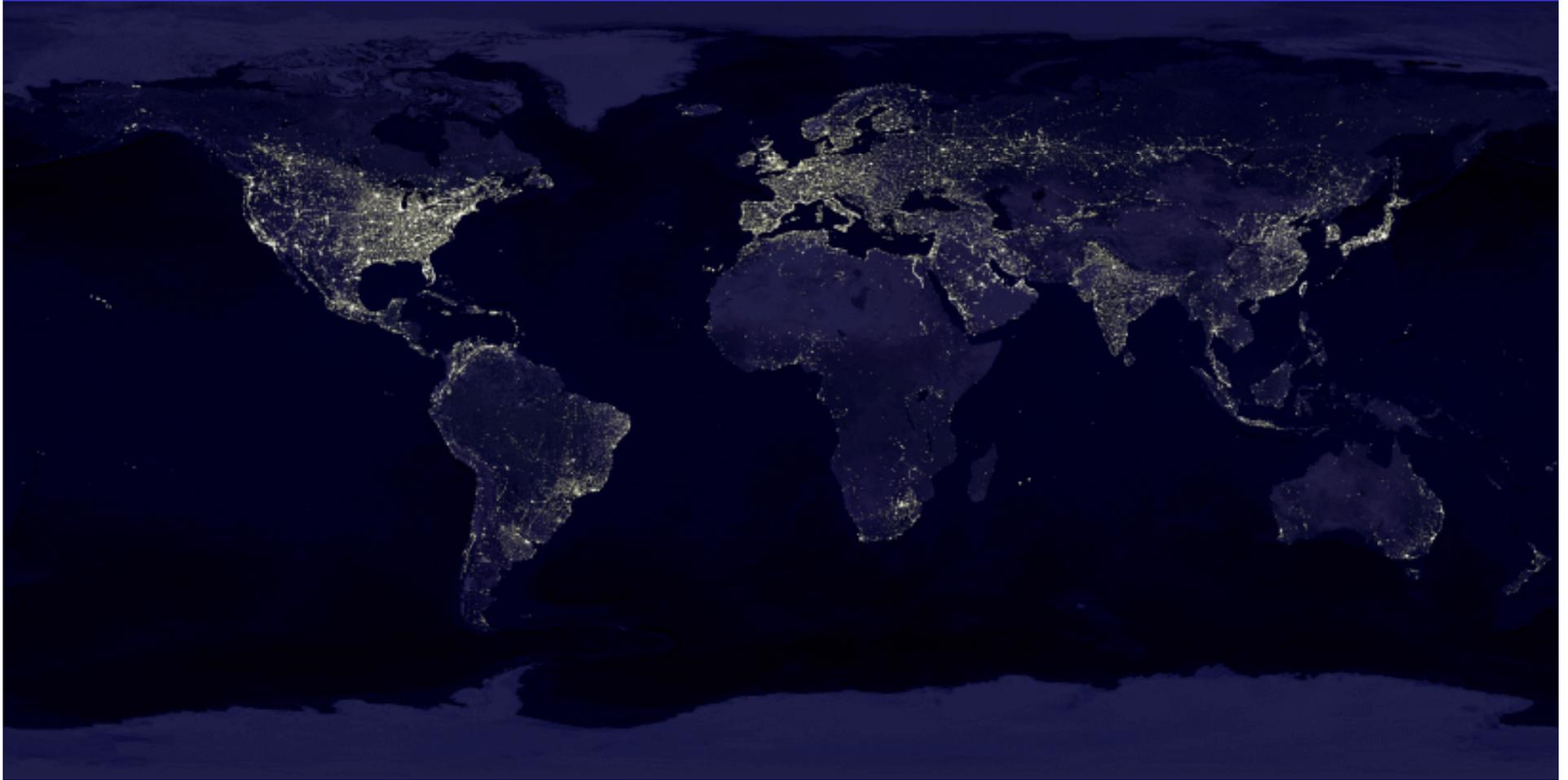


Orbit Trade Study: Eccentricity

- 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

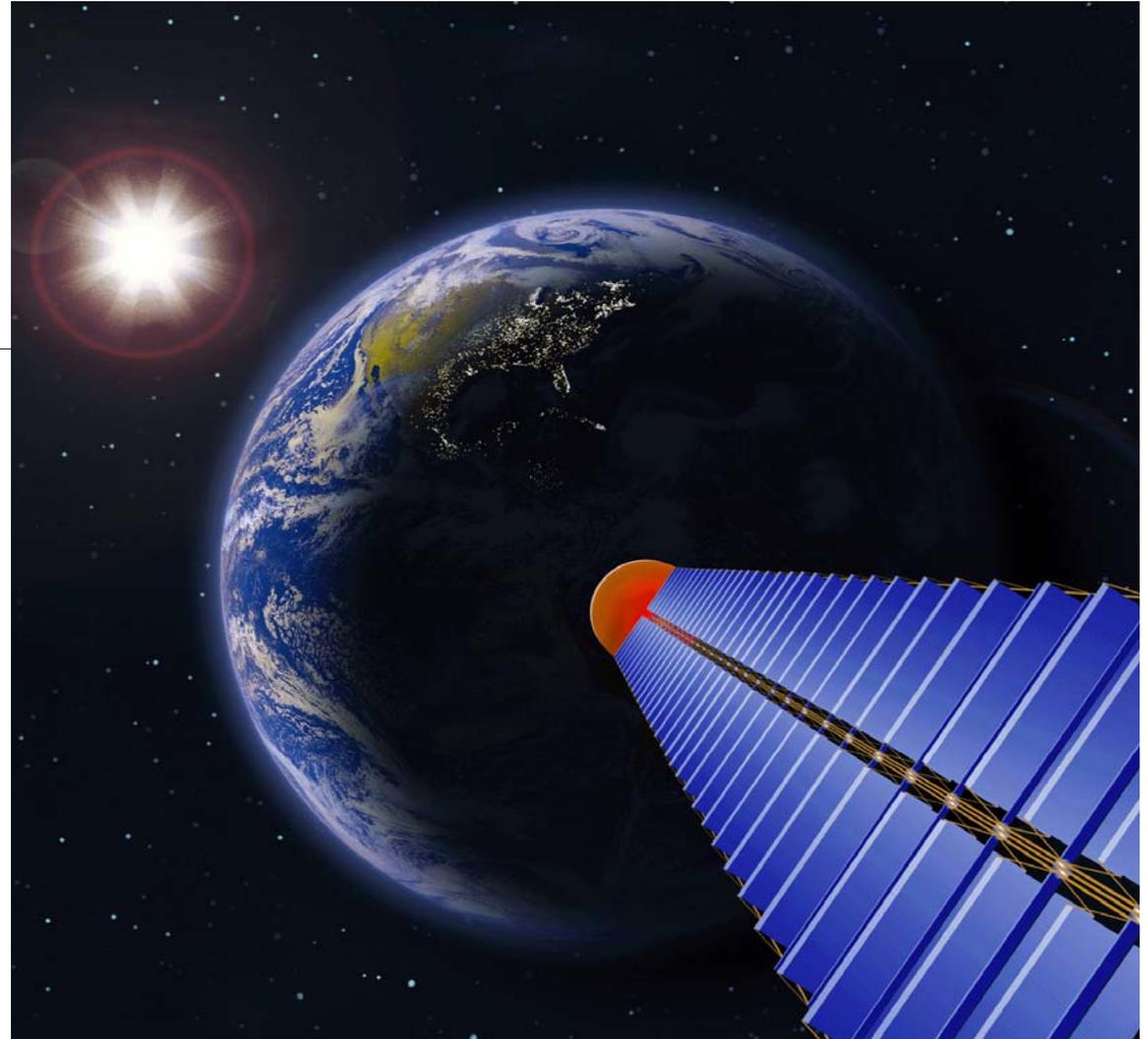


Remote Sensing of Current Global Power Consumption:
A Composite Satellite Photograph of the Earth at Night

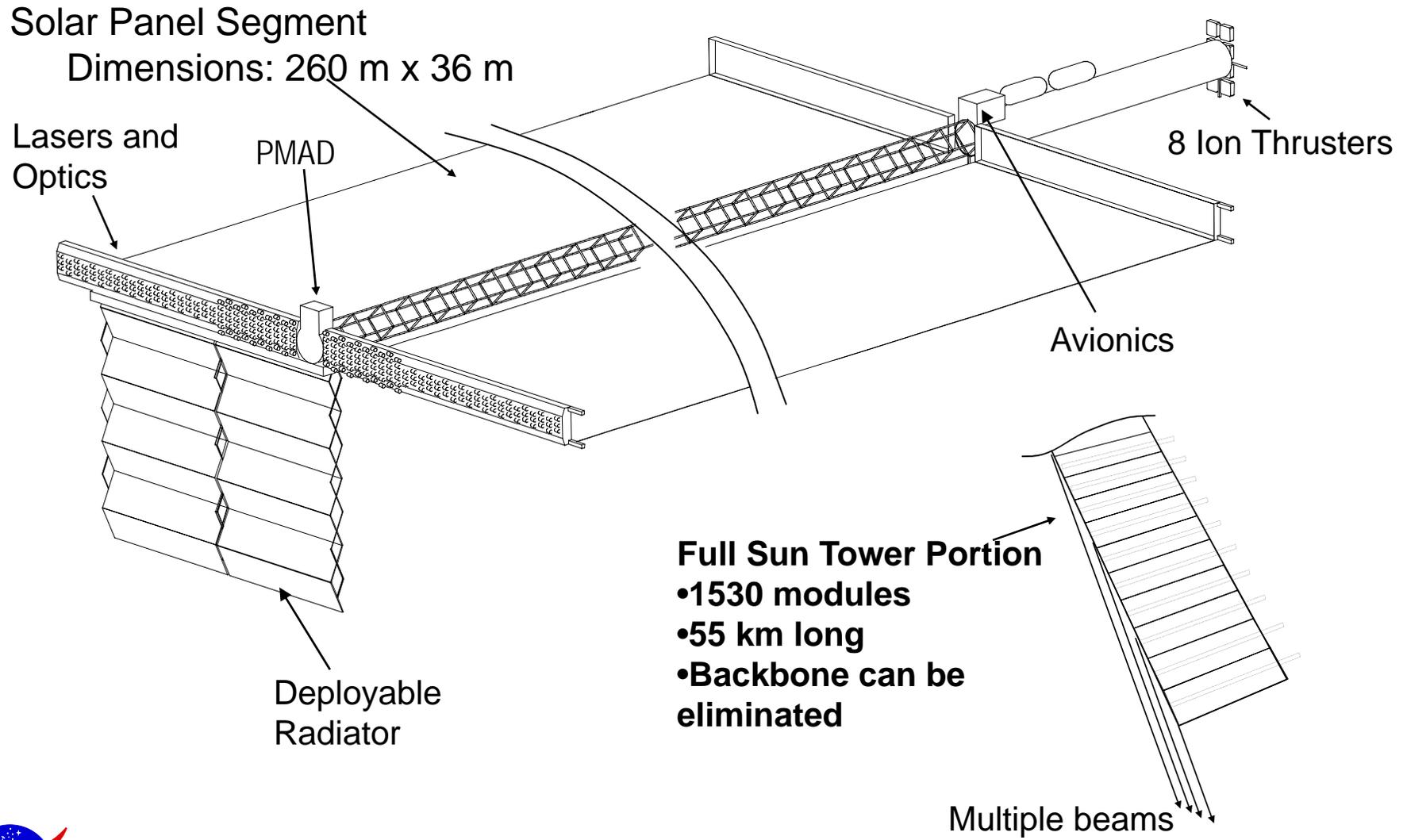


Initial Photovoltaic / Microwave SPS GEO Sun Tower Conceptual Design

- “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



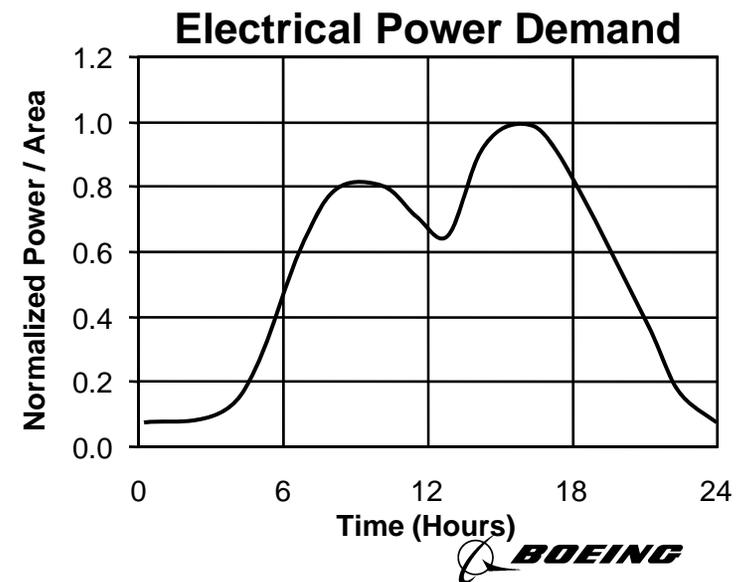
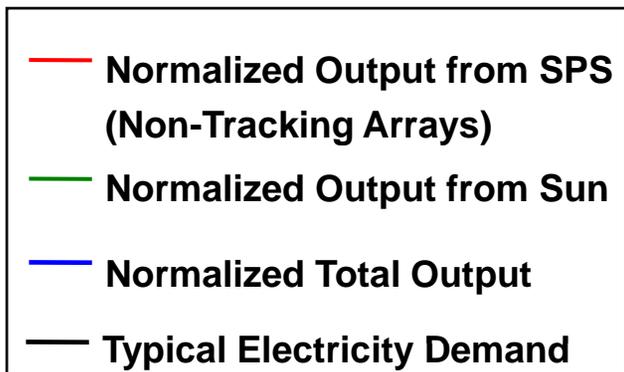
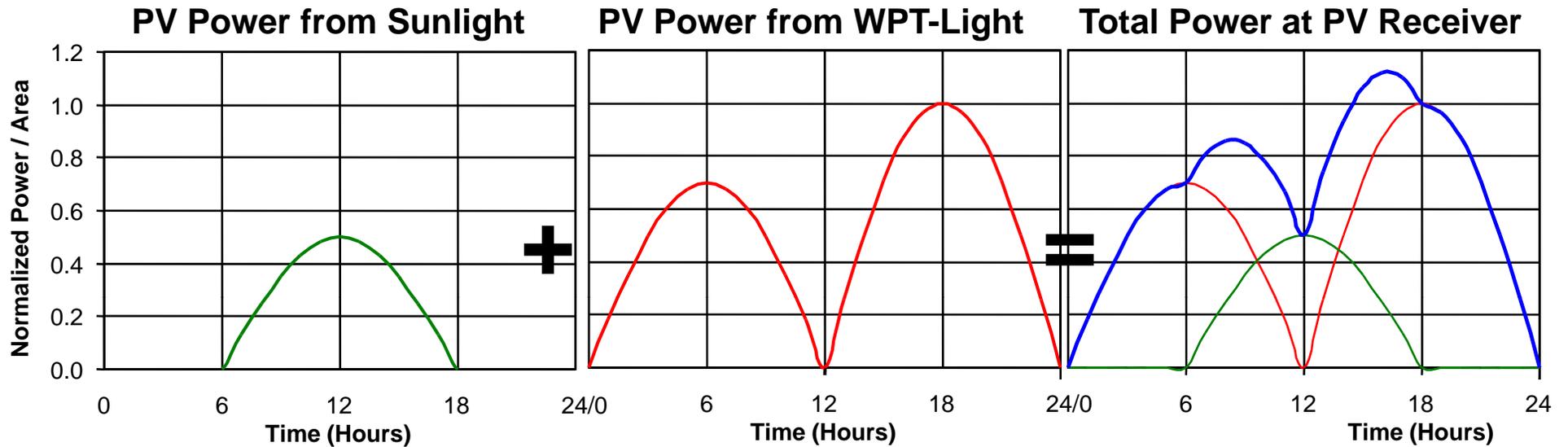
Synergy Between Sunlight and Laser-PV WPT for Terrestrial Photo-Voltaic Power Production

- 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



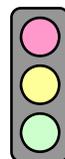
Sunlight + Laser-PV WPT = ~ Power Requirement

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

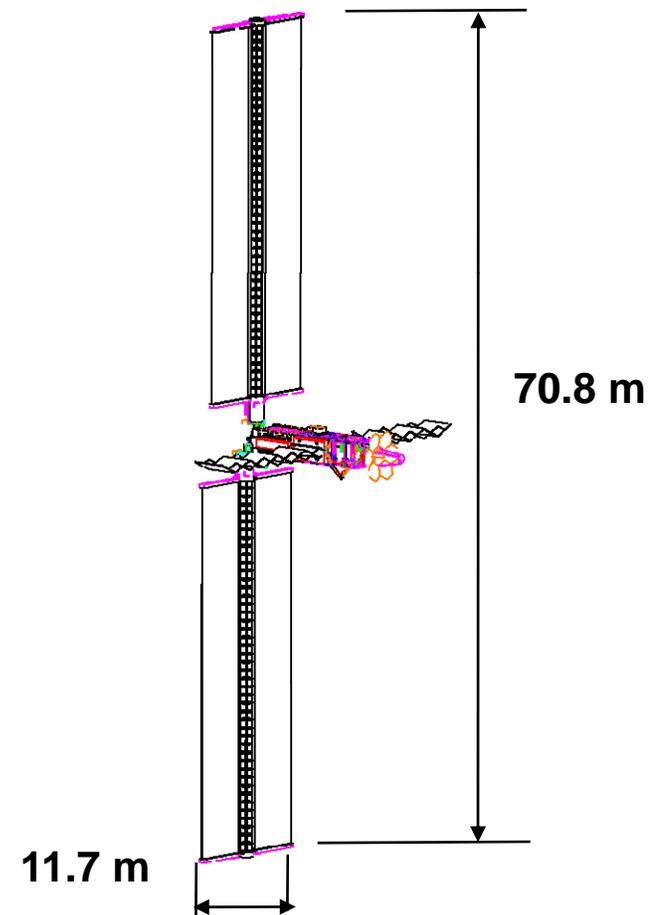
| ATTRIBUTE | PHOTOVOLTAIC | SOLAR DYNAMIC |
|--|---------------------------------|---------------------------------------|
| Solar Collector Area | Moderately high, but improving | Low |
| Radiation Tolerance | Degrades | Excellent |
| Specific Power | Moderate | Low, but should be high in far term |
| 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

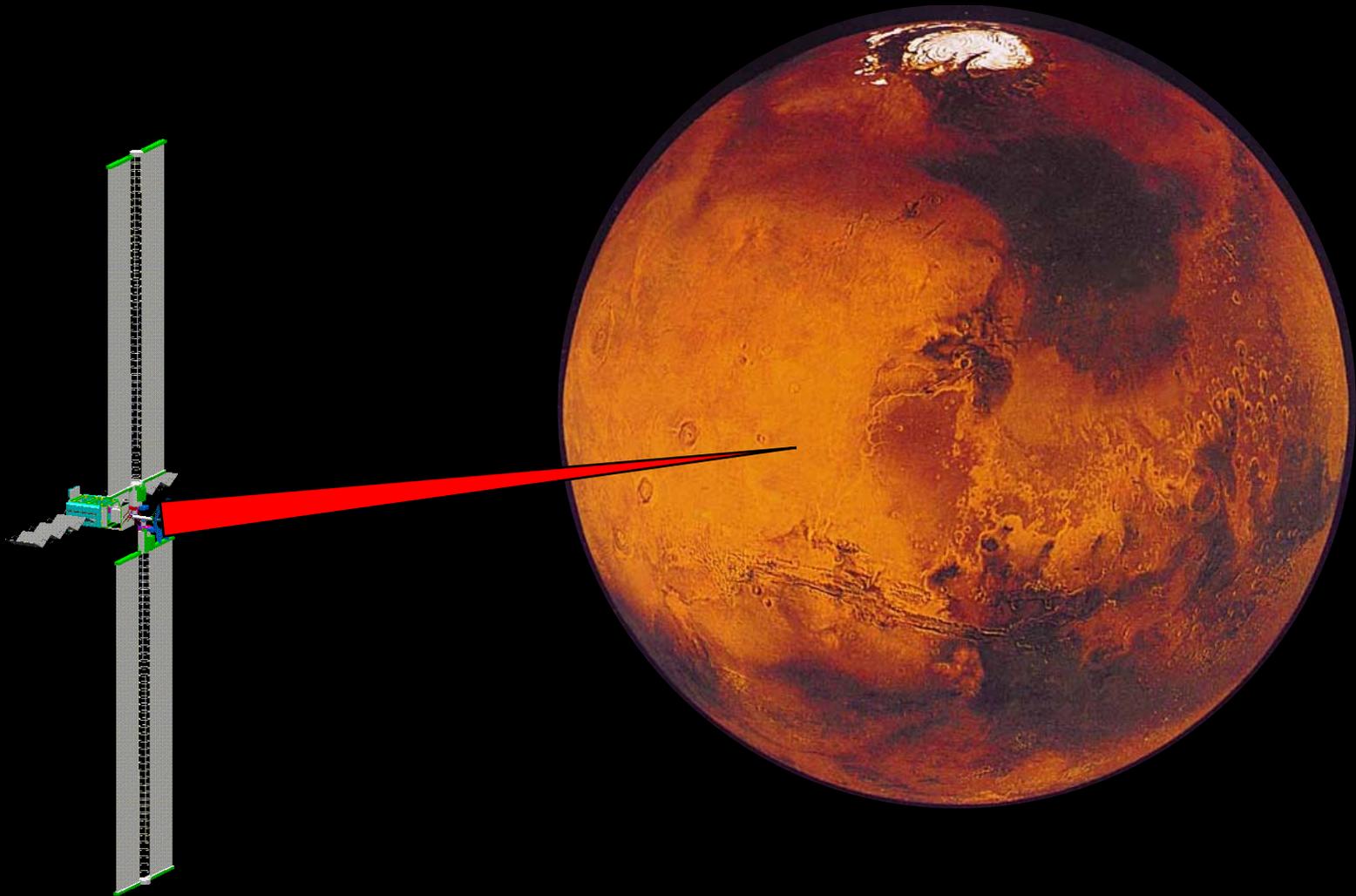


ISS with IEA Solar Panels Fully Deployed

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



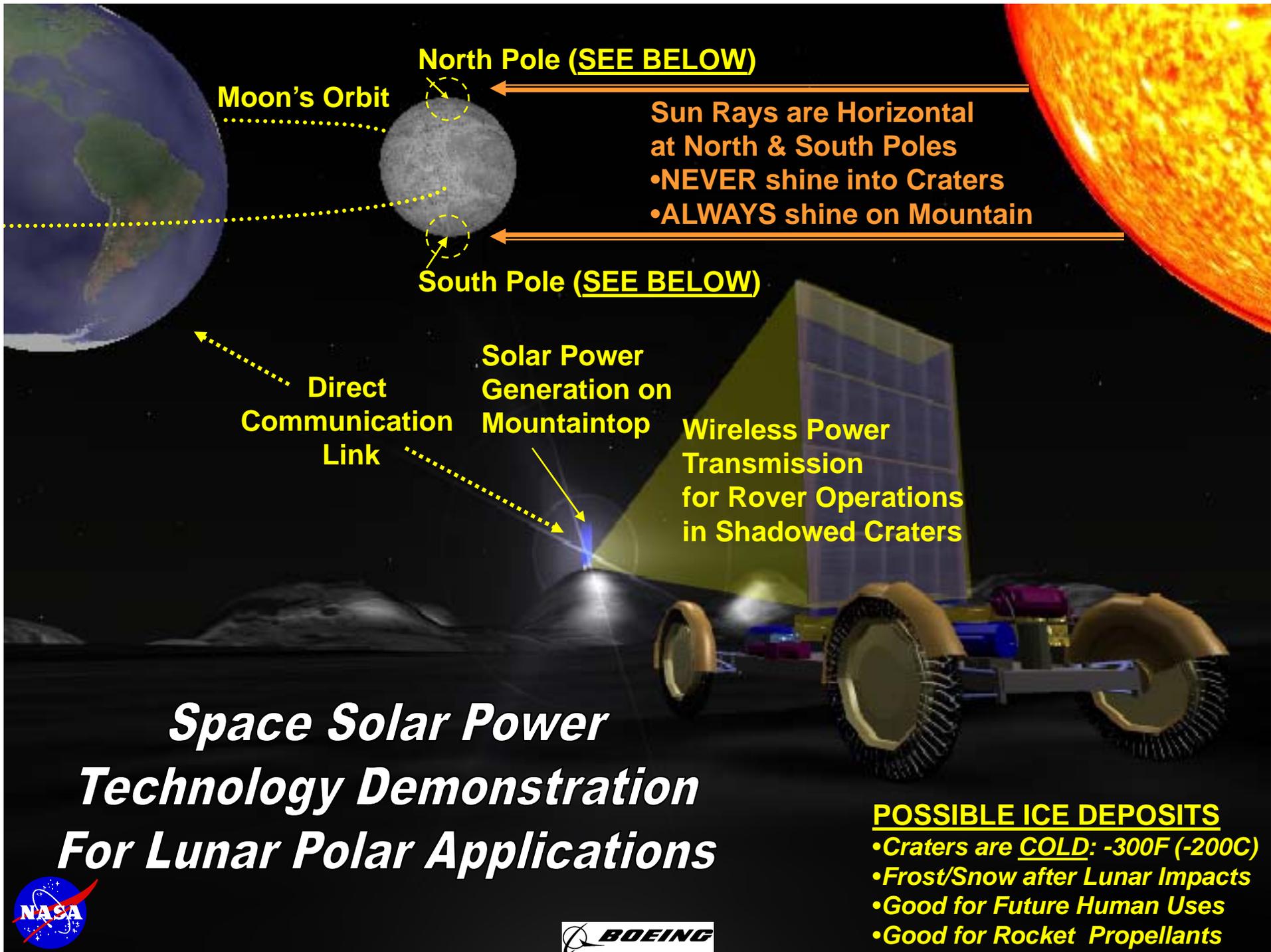
MSC-1A: Lunar and Mars Power (LAMP) Application Laser WPT to Photovoltaics on the moon or Mars



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

