Wireless Power Transmission Options for Space Solar Power

Seth Potter¹, Mark Henley¹, Dean Davis¹, Andrew Born¹, Martin Bayer¹, Joe Howell², and John Mankins³

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

Abstract for a presentation to be given at the  
State of Space Solar Power Technology Workshop  
Lake Buena Vista, Florida  
2-3 October 2008

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.
Wireless Power Transmission Options for Space Solar Power

Seth Potter (1), Mark Henley (1), Dean Davis (1), Andrew Born (1), Martin Bayer (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

State of Space Solar Power Technology
Lake Buena Vista, Florida
2-3 October 2008
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

Solar Panel Segment
Dimensions: 260 m x 36 m

Lasers and Optics
PMAD

Deployable Radiator

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

Avionics

8 Ion Thrusters

Multiple beams
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 (space solar power satellites, terrestrial solar, nuclear, fossil fuel)
## Boeing Trade Studies: Assessment Criteria

<table>
<thead>
<tr>
<th>Trade Categories</th>
<th>Assessment Criteria</th>
</tr>
</thead>
<tbody>
<tr>
<td>Raw Materials Source</td>
<td>Accessibility (distance and acquisition)</td>
</tr>
<tr>
<td>Manufacturing and Integration Location</td>
<td>Accessibility (distance and acquisition)</td>
</tr>
<tr>
<td>Deployment Location</td>
<td>Accessibility (distance and acquisition)</td>
</tr>
<tr>
<td>Space Transportation</td>
<td>Unavailability</td>
</tr>
<tr>
<td>Energy Conversion</td>
<td>Conversion efficiency</td>
</tr>
<tr>
<td>Energy Transmission</td>
<td>Transmission energy efficiency</td>
</tr>
<tr>
<td>Energy Storage</td>
<td>Storage efficiency</td>
</tr>
<tr>
<td>Electronic Components</td>
<td>Memory size</td>
</tr>
<tr>
<td>Architecture</td>
<td>Redundancy</td>
</tr>
<tr>
<td>Command and Control Data Links</td>
<td>Bandwidth Transmission range</td>
</tr>
<tr>
<td>Attitude and Orbit Control</td>
<td>Mass fraction</td>
</tr>
<tr>
<td>Structural Concept</td>
<td>Mass fraction</td>
</tr>
<tr>
<td>Thermal Management</td>
<td>Mass fraction</td>
</tr>
<tr>
<td>Confining</td>
<td>Mass fraction</td>
</tr>
<tr>
<td>Element Connection</td>
<td>Mass fraction</td>
</tr>
<tr>
<td>System Configuration</td>
<td>Redundancy</td>
</tr>
<tr>
<td>Manufacturing, Assembly, and Maintenance Operations</td>
<td>Number of neededcrew</td>
</tr>
</tbody>
</table>

### Key
- **Potential Showstopper**
- **Highly Critical Decision Driver**
- **Critical Decision Driver**
- **Tiebreaker Only**
# Boeing Trade Studies: Ratings of Options

<table>
<thead>
<tr>
<th>Trade Categories</th>
<th>Raw Materials Source</th>
<th>Manufacturing and Integration Location (may be separate)</th>
<th>Deployment Location</th>
<th>Space Transportation</th>
<th>Energy Conversion</th>
<th>Energy Transmission</th>
<th>Energy Storage</th>
<th>Electronic Components</th>
<th>Electronics Architecture</th>
<th>Command and Control Data Links</th>
<th>Attitude and Orbit Control</th>
<th>Structural Concept</th>
<th>Thermal Management</th>
<th>Concentrator</th>
<th>Element Connection</th>
<th>System Configuration</th>
<th>Manufacturing, Assembly and Maintenance Operations</th>
<th>Key</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Low Earth Orbit (LEO)</td>
<td>Sun Synchronous Orbit (SSO)</td>
<td>Earth-Moon Libration points and halo orbits</td>
<td>Electric rockets</td>
<td>Conventional launchers</td>
<td>Batteries</td>
<td>Radiofrequency applications</td>
<td>Distributed</td>
<td>Radiofrequency Laser (stable/insulated)</td>
<td>Reaction control systems</td>
<td>Solid members/Inflatable</td>
<td>Passive cooling</td>
<td>Cylindrical</td>
<td>RigidlyAttached</td>
<td>Mechanically/integrated/identical modules</td>
<td>Purely Human</td>
<td>Baseline (Most Preferred) Option</td>
</tr>
</tbody>
</table>
**Boeing Trade Studies: Ratings of Options**

<table>
<thead>
<tr>
<th>Raw Materials Source</th>
<th>NearEarth Objects</th>
<th>Moon</th>
<th>Earth</th>
<th>Sun Synchronous Orbit</th>
<th>Medium Earth Orbit</th>
<th>High Earth Orbit</th>
<th>Geostationary Earth Orbit</th>
<th>Near Space</th>
<th>Earth-Moon Libration points and Halo Orbits</th>
<th>Earth-Sun Libration points and Halo Orbits</th>
<th>Lunar Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>Deployment Location</td>
<td>Low Earth Orbit (LEO)</td>
<td>Sun Synchronous Orbit (SSO)</td>
<td>Medium Earth Orbit (MEO)</td>
<td>High Earth Orbit (HEO)</td>
<td>Geostationary Earth Orbit (GEO)</td>
<td>Near Space</td>
<td>Earth-Moon Libration points and Halo Orbits</td>
<td>Earth-Sun Libration points and Halo Orbits</td>
<td>Lunar Surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Space Transportation</td>
<td>Low Earth Orbit (LEO)</td>
<td>Sun Synchronous Orbit (SSO)</td>
<td>Medium Earth Orbit (MEO)</td>
<td>High Earth Orbit (HEO)</td>
<td>Geostationary Earth Orbit (GEO)</td>
<td>Near Space</td>
<td>Earth-Moon Libration points and Halo Orbits</td>
<td>Earth-Sun Libration points and Halo Orbits</td>
<td>Lunar Surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Energy Transmission</td>
<td>Laser Lithotrope/Maser</td>
<td>Microwave Maser</td>
<td>Microwave Laser</td>
<td>Microwave Laser</td>
<td>Microwave Laser</td>
<td>Microwave Laser</td>
<td>Microwave Laser</td>
<td>Microwave Laser</td>
<td>Microwave Laser</td>
<td></td>
<td></td>
</tr>
<tr>
<td>System Configuration</td>
<td>Functionally Integrated Chassis</td>
<td>Monolithic Elements with separate functions</td>
<td>Monolithic Elements with separate functions</td>
<td>Monolithic Elements with separate functions</td>
<td>Monolithic Elements with separate functions</td>
<td>Monolithic Elements with separate functions</td>
<td>Monolithic Elements with separate functions</td>
<td>Monolithic Elements with separate functions</td>
<td>Monolithic Elements with separate functions</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

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

*Initial focus is on major drivers of system design and cost*
Sizing of Receiver Array

Array sized to main beam lobe collects 84% of total power

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 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)

Transmitter Diameter (m) for 35,786 km SPS & 500 m rectenna
Transmitter Diameter (m) for 20,200 km SPS & 500 m rectenna
Transmitter Diameter (m) for 3,000 km SPS & 500 m rectenna
Transmitter Diameter (m) for 1,000 km SPS & 500 m rectenna
Transmitter Diameter (m) for 400 km SPS & 500 m rectenna
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)
• 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
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

PV Power from Sunlight
PV Power from WPT-Light
Total Power at PV Receiver

Normalized Output from SPS (Non-Tracking Arrays)
Normalized Output from Sun
Normalized Total Output
Typical Electricity Demand
## WPT Wavelength Trade for SSP

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

### Area of Significant Concern
- **Pink**

### Intermediate Area
- **Yellow**

### Area of Significant Benefit
- **Green**
## Power Generation Trade for SSP

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

**Legend:**
- **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.
25

Wireless Power Transmission for Rover Operations in Shadowed Craters

Solar Power Generation on Mountaintop

Direct Communication Link

Moon’s Orbit

North Pole (SEE BELOW)

Sun Rays are Horizontal at North & South Poles

• NEVER shine into Craters

• ALWAYS shine on Mountain

South Pole (SEE BELOW)

Solar Power Generation on Mountaintop

Wireless Power Transmission for Rover Operations in Shadowed Craters

POSSIBLE ICE DEPOSITS

• Craters are COLD: -300F (-200C)

• Frost/Snow after Lunar Impacts

• Good for Future Human Uses

• Good for Rocket Propellants

Space Solar Power Technology Demonstration For Lunar Polar Applications
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