Overview of Small and Large-Scale Space Solar Power Concepts

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An overview of space solar power studies performed at the Boeing Company under contract with NASA will be presented. The major concepts to be presented are:

1. Power Plug in Orbit: this is a spacecraft that collects solar energy and distributes it to users in space using directed radio frequency or optical energy. Our concept uses solar arrays having the same dimensions as ISS arrays, but are assumed to be more efficient. If radiofrequency wavelengths are used, it will necessitate that the receiving satellite be equipped with a rectifying antenna (rectenna). For optical wavelengths, the solar arrays on the receiving satellite will collect the power.

2. Mars Clipper / Power Explorer: this is a solar electric Mars transfer vehicle to support human missions. A near-term precursor could be a high-power radar mapping spacecraft with self-transport capability. Advanced solar electric power systems and electric propulsion technology constitute viable elements for conducting human Mars missions that are roughly comparable in performance to similar missions utilizing alternative high thrust systems, with the one exception being their inability to achieve short Earth-Mars trip times.

3. Alternative Architectures: this task involves investigating alternatives to the traditional solar power satellite (SPS) to supply commercial power from space for use on Earth. Four concepts were studied: two using photovoltaic power generation, and two using solar dynamic power generation, with microwave and laser power transmission alternatives considered for each. All four architectures use geostationary orbit.

4. Cryogenic Propellant Depot in Earth Orbit: this concept uses large solar arrays (producing perhaps 600 kW) to electrolyze water launched from Earth, liquefy the resulting hydrogen and oxygen gases, and store them until needed by spacecraft.

5. Beam-Powered Lunar Polar Rover: a lunar rover powered by a microwave or laser beam can explore permanently shadowed craters near the lunar poles to search for water ice and other frozen volatiles. Near such craters are mountain peaks and highlands that are in near permanent sunlight. Power can be beamed from a collector on a sunlit mountain or crater rim to a rover inside a crater.

Near-term applications of space solar power technology can therefore pave the way toward large-scale commercial power from space.
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Boeing Has Studied Several Space Solar Power-Related Concepts

Power Plug in Orbit

Mars Clipper

Alternative SPS Architectures

Cryogenic Propellant Depot

Beam-Powered Lunar Rover
Power Plug
(Space-to-Space Power Beamer)

- Demonstrates deployment of space solar power modules
- Demonstrates solar electric propulsion
- Demonstrates solar-powered wireless power transmission
  - Efficient power generation
  - Efficient power transmission
  - Effective heat dissipation
  - Accurate pointing of beam
  - Use ISS-compatible arrays; current ISS array pair produces 61.5 kW
    > Advanced cells may increase this to ~120 kW
    > For 30% power conversion efficiency, this yields ~36 kW in beam
- Mass: approximately 20 metric tonnes

Array dimensions are similar to ISS

70.8 m

11.7 m
Power Plug: Additional Applications

- Power Plug can be a spacecraft bus carrying a payload which can be:
  - Wireless power transmission system
  - Communications package
  - Science or exploration payload
- Missions and demonstrations can include:
  - Wireless power transmission (WPT) demonstrations
    > Space to space
    > Space to planetary surface
  - Other advanced technology demonstrations
    > Advanced solar cells
    > Solar electric propulsion
  - High power communications satellite
  - Solar electric transfer of WPT, scientific, or communications package from LEO to:
    > MEO
    > GEO
    > Moon
“Power Explorer” Radar Mapping Spacecraft

- Approach: Design spacecraft based on two half-size segments of SSP Sun Tower
- Dimensions: Two pairs 52 m x 31 m solar panels (four panels total) with 32 m x 8 m transmitter/receiver (assembled from two 16 m x 8 m panels)
- Power source: onboard solar cells power a 5.8 GHz radar beam and Hall Effect Thrusters at a peak total power level of ~4 MW near Earth
Human Mars missions can consist of 3 vehicles:

- **Cargo 1 Transfer Stage**: Unpiloted Lander, consisting of
  - Surface habitat
  - Equipment
  - Surface rover
  - Consumables
  - Aeroshell: not shown in illustration
  - 57371 kg total mass

- **Cargo 2 Transfer Stage**: Piloted Ascent/Descent Stage
  - Aeroshell: not shown in illustration
  - 57,771 kg total mass

- **Piloted Transfer Stage**
  - 268 MT IMLEO for expendable
  - 501 MT IMLEO for reusable
# Mars Clipper
## Piloted Mission Parameters

<table>
<thead>
<tr>
<th>Phase</th>
<th>Initial Orbit (km)</th>
<th>Final Orbit (km)</th>
<th>Mass Initial (mt)</th>
<th>Mass Propel (mt)</th>
<th>Mass Final (mt)</th>
<th>Time (days)</th>
<th>Tot Mission Duration (days)</th>
<th>Delta-V (km/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LEO to Earth Escape</td>
<td>300 x 300</td>
<td>E Escape</td>
<td>501</td>
<td>153</td>
<td>347</td>
<td>267</td>
<td>267</td>
<td>7.15</td>
</tr>
<tr>
<td>Earth Escape to Mars Orbit Capture</td>
<td>E Escape</td>
<td>250 x 33,000 Mars</td>
<td>347</td>
<td>114</td>
<td>232</td>
<td>255</td>
<td>522</td>
<td>8.16</td>
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<tr>
<td>Mars Surface Stay</td>
<td>250 x 33,000 Mars</td>
<td>E Escape</td>
<td>232</td>
<td>0</td>
<td>232</td>
<td>600</td>
<td>1122</td>
<td>0</td>
</tr>
<tr>
<td>Mars Capture Orbit to Matching Earth Vel</td>
<td>E Escape</td>
<td>300 x 300</td>
<td>232</td>
<td>71</td>
<td>160</td>
<td>156</td>
<td>1278</td>
<td>8.16</td>
</tr>
<tr>
<td>Matching Earth Arrival Vel to Earth LEO</td>
<td>E Escape</td>
<td></td>
<td>300 x 300</td>
<td>160</td>
<td>42</td>
<td>74</td>
<td>1352</td>
<td>7.15</td>
</tr>
</tbody>
</table>
## WPT Frequency Trade for SSP Alternative Architectures

<table>
<thead>
<tr>
<th>ATTRIBUTE</th>
<th>MICROWAVES</th>
<th>OPTICAL WAVELENGTHS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aperture Size</td>
<td>Large, so system must be large</td>
<td>Small, gives flexibility of system design</td>
</tr>
<tr>
<td>Interference</td>
<td>Electromagnetic spectrum</td>
<td>None, except perhaps astronomy</td>
</tr>
<tr>
<td>Rain, Cloud Attenuation</td>
<td>Lower frequencies can penetrate clear air, clouds, and light rain</td>
<td>Optical wavelengths are attenuated by clouds and rain</td>
</tr>
<tr>
<td>Legal Issues</td>
<td>FCC, NTIA, ITU</td>
<td>ABM treaty, if power density high</td>
</tr>
<tr>
<td>Dual Use of Infrastructure</td>
<td>Rectennas used for SSP only (possibly communication)</td>
<td>Terrestrial PV arrays: can receive sunlight</td>
</tr>
<tr>
<td>Dual Use of Land</td>
<td>Crops or PV under rectennas</td>
<td>PV arrays on rooftops, etc.</td>
</tr>
<tr>
<td>Perception Issues</td>
<td>Public fears of &quot;cooking&quot;</td>
<td>Governments may fear weapons application</td>
</tr>
<tr>
<td>Safety</td>
<td>Safe, but must keep aircraft out of beam</td>
<td>Safe, if power density is kept low</td>
</tr>
<tr>
<td>Efficiency of space segment</td>
<td>High</td>
<td>Improving</td>
</tr>
<tr>
<td>Efficiency of ground segment</td>
<td>High</td>
<td>Improving</td>
</tr>
<tr>
<td>Traceability</td>
<td>Heritage to communications and radar</td>
<td>MSC 1 and 3</td>
</tr>
<tr>
<td>PMAD</td>
<td>Heavy due to centralized WPT</td>
<td>Light; WPT can be distributed</td>
</tr>
</tbody>
</table>
Solar Power Satellite Alternative Architectures

• Four options considered, based on power generation and power transmission methods:
  – Photovoltaic power generation, microwave power transmission;
  – Photovoltaic power generation, laser power transmission;
  – Solar dynamic power generation, microwave power transmission;
  – Solar dynamic power generation, laser power transmission.
• All four options use geostationary orbit.
Photovoltaic / Microwave SPS
GEO Sun Tower Concept

- Power transmitted: 3 GW
- Power into terrestrial grid: 1.2 GW
- Solar array “wing span”: 500 m
- 355 array pairs.
- Total length: 16 km
- Transmitter array is 500 m in diameter
- Power transmission frequency: 5.8 GHz
- Mass: 26,500 metric tonnes (includes LEO-to-GEO self-transport capability)
- Mass: 22,900 metric tonnes (not including self-transport capability)
Photovoltaic Laser SPS Concept

Solar Panel Segment Dimensions:
260 m x 36 m

Power Mgmt. and Distribution
Avionics / Propulsion
Diode Laser and Optics
Deployable Radiator

Full Sun Tower Portion:
- Each segment has its own laser
- Backbone can be eliminated
- 1530 modules
- 55 km long
- Mass: ~46,000 MT with self-transport capability (~35,000 without)
Laser SPS and Terrestrial PV: Possible Synergy

- Large terrestrial photovoltaic power plants may already be in place in desert locations (Mojave, Sahara, Gobi, etc.) by the time SPSs are deployed
- Laser SPS provides an additional source of illumination to these arrays
  - Most promising laser technology has wavelengths that are near bandgap of common PV cells, so SPS illumination is converted more efficiently than sunlight
- Gravity gradient-stabilized SPSs are in peak insolation at \( \sim 6 \) AM and \( \sim 6 \) PM, with shadowing or cosine loss at mid-day and midnight
  - Mass and complexity of gimbaled arrays may add little extra power at these times
  - Both sides of SPS PV arrays can be light-sensitive, but back side may lose \( \sim 30\% \) power due to darkening of Kapton substrate
- Laser illumination plus ambient sunlight combine at terrestrial PV array to approximate the daily electricity demand pattern
**Gimbaled vs. Rigid Sun Tower**

**Gimbaled Array**
- Gimballing mechanisms avoid cosine losses
- Shadowing losses around noon & midnight cannot be avoided
- Shadowing complicates cell arrangement and PMAD operation

**Rigid Array**
- Cosine losses around noon & midnight cannot be avoided
- Balanced electrical and thermal loads
- Closer packing reduces overall length

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**BOEING**
Power Output of Laser SPS Can Be Combined With Ambient Sunlight to Follow Demand

Terrestrial PV Array Output
(Array Spacing = 1/4 Array Width)

Normalized Average
Output from SPS (Non-Tracking Arrays)
Normalized Average
Output from SPS (Tracking Arrays)

Daily Electricity Demand Pattern

* Highest power usage is typically between 2:00 pm - 6:00 pm
* Power value (and price) increases substantially at peak time
* Power delivered at peak time avoids inefficiency & infrastructure of ground storage

Terrestrial PV Array Output: Sun + SPS Power
Normalized to Peak Output from SPS w/o Sun

Terrestrial PV Array Output: Sun + SPS Power
Normalized to Peak Output from SPS w/o Sun
(1 Hour Time Offset)
Diffraction-Limited Beam Intensity from a Uniformly Illuminated Circular Aperture

Normalized Beam Intensity

Normalized Beam Intensity (dB)

Normalized Beam Intensity -- vertical scale expanded to show sidelobes
Building Top-Hat Beam Profile with Overlapping Out-of-Phase Laser Beams

Notes:
- Horizontal scale not held constant in plots.
- Geometric arrangement of multiple beams not necessarily configured to minimize edge effects.
- Diffraction-limited beams assumed.
# Power Generation Trade for SPS Alternative Architectures

<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>Degraded</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</td>
<td>Extensive use on satellites</td>
<td>Vacuum chamber only</td>
</tr>
<tr>
<td>Environment</td>
<td>Extensive use on satellites</td>
<td></td>
</tr>
</tbody>
</table>
Solar Dynamic / Microwave SPS
GEO Abacus-Like POP Concept

326 Units

Mass: 28,000 metric tonnes
(does not have self-transport capability)

Reflector:
520 x 690 m

Transmitting Antenna: 500 m

3000 m

2598 m
Solar Dynamic / Laser SPS
GEO Abacus-Like SPS Concept

- 20 modules per "beam aperture"
- 20 x 16 grid, 320 units
- 2.8 GW / 320 units = 8.75 MW / unit
- Solar concentrator diameter: 160 m
- Total mass: 35,000 metric tonnes
Propellant Production Depot Design
Includes Seven Key Subsystems

1. LOX/LH2 Storage Tanks
2. Transfer Vehicle Docking Ports
3. Radiators
4. Solar Arrays
5. Water Docking Port
6. Water Storage Tanks
7. Electrolysis System
System Design Features of the Propellant Production Depot

12m long LOX/LH$_2$ tanksets -- gravity gradient propellant settling

- ENTECH Stretched Lens Array (SLA's)
  - Sized for 706kWe (635kWe delivered to bus)
  - Inflatable abacus structure

- Power Management & Distribution (PMAD)
  - 150V
  - No converters at the arrays
  - Two power conducting slip rings

- 8 Delta IV Heavy-class tanksets
  - 500 MT LOX & LH$_2$ per year
  - Stoichiometric 8:1 mixture ratio

- Composite truss structure

- Robotics including infrastructure

- Stationkeeping & attitude control
  - SEP 0.5N thrusters
  - 50kWe Hall thrusters
  - CMGs
  - Attitude sensors
  - Krypton stationkeeping propellant for 10 years

24 10x3m subarrays

400 km circular equatorial orbit

LOx tank is mounted inboard, LH$_2$ tank is mounted outboard for greater microgee force
Propellant Production Depot Configuration Dimensions
Space Solar Power
Technology Demonstration
for Lunar Polar Applications

- Technology for Laser-Photo-Voltaic Wireless Power Transmission (Laser-PV WPT) has been developed for lunar polar applications by Boeing and NASA Marshall Space Flight Center.

- A lunar polar mission could demonstrate and validate laser-photovoltaic wireless power transmission 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 (and Earth).
  - A photovoltaic-powered rover could use sunlight, when available, and laser light, when required, to explore a wide range of lunar polar terrain.
Radar-Derived Topography of the Moon’s North and South Poles

- Note Difference in Vertical Scale!!!

North Pole > 85 degrees

South Pole > 85 degrees
Laser Range Depends on Topography
Transmitter on lunar mountain could beam power > 100 km

120 km Range (to horizon)
6 km high mountain
1 km high mountain, 50 km Range
Relay Mirror Option
Deep Crater
Further Range

WPT from Lunar Mountaintop
(spherical Moon, vertical scale exaggerated)
Laser Range from Example Mountain-Top (Direct Line-of-Sight from Point E)

Maximum Line-of-Sight Range from Mountain “E”
Rover for Demonstration of Wireless Power Transmission Technology
Key Points and Conclusions (1 of 3)

- SSP technology can enable space exploration and development in the near term
  - Power Plug can be deployed from existing launch vehicles
  - Mars Clipper and Propellant Depot can bridge the gap between Power Plug and commercial SSP
  - Near-term applications provide top-level traceability to commercial SSP

- Photovoltaic microwave SSP systems are efficient, easily assembled, and can beam power through clouds and light rain
  - Microwave WPT technology is relatively mature
  - Need specialized ground asset: rectenna
  - Cost to first power (minimum system size) is large

- Laser SSP systems allow smooth transition from conventional power to SSP
  - Small aperture size allows for low cost to first power
  - System upgrades and degrades gracefully
  - Can use independently beneficial ground asset: terrestrial PV arrays, which may already be in place
Key Points and Conclusions (2 of 3)

• Laser SSP systems open up new architecture options
  – Lower efficiencies of current and near-term technology would seem to necessitate higher satellite masses than microwave systems; however, specific power may be competitive because
    > Small apertures may minimize WPT system mass
    > Lasers can be distributed, minimizing power management & distribution mass
  – Narrow beams can overlap to generate a "top hat" energy profile
    > Allows for better use of land at receiver site
  – Lower land use requirement facilitates multiple receiver sites to mitigate weather outages
  – Shape of energy distribution can be tailored to available ground site
  – Gravity gradient-stabilized Sun Tower-like architectures may make more sense for lasers than for microwave systems
    > Cosine loss at midday may be mitigated by ambient sunlight at receiver site
    > Use of rotating arrays and long tether may not mitigate cosine loss sufficiently to justify additional weight and complexity; rigid arrays with both sides able to convert sunlight to electricity may be preferable
Key Points and Conclusions (3 of 3)

- Laser and microwave SSP systems may have differing design drivers
  - Microwaves require large transmit/receive apertures, so WPT is major design driver
  - Laser performance is temperature-dependent, so thermal management may be major design driver
- Cryogenic propellant depots can enable the development of large-scale (but sub-SPS) space power systems and support the exploration and development of space
- Beam-powered lunar rover technology can pave the way to SPS, while prospecting for resources at the lunar poles