Visualizing Wireless Transfer of Power: Proposal for A Five-Nation Demonstration by 2020

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Proposal

Our proposal is to conduct a near-term multinational experiment that develops needed knowledge, provides a visible demonstration, and builds customer confidence in the viability of SSP.

• Use the International Space Station (~400km altitude) as the primary platform from which power will be beamed to several terrestrial sites as a demonstration and for scientific data collection.

• Second spacecraft at 2000 km, used as a relay for beamed power delivery from the ground and from the ISS.

• Ground stations in five or more nations using one or more millimeter wave frequency windows for atmospheric transmission.
Objectives

1. Science Objectives
2. Technology Demonstrations
3. Public policy exercise
4. Public education objectives
5. Build momentum . . .
Summary

This proposal springs from the belief that to make Space Solar Power a significant component of global energy supply (4000 GWe), it must become a global endeavor.

This will involve:
- All nations with any interest, as participants;
- A synergistic partnership between many industries and markets;
- Private firms, public multinational corporations,
- Civilian space agencies, energy agencies, environmental and climate protection agencies, military and security interests.

Our proposal is to start along a roadmap towards
• Early demonstrations with scientific and technical value;
• Research and development;
• Public education;
• Public policy initiatives;
• Global collaboration framework; and
• Public-private partnerships.
Background

Major Issues in developing Space Based Solar Power are:
1. Specific Power (electric power delivered per unit mass in orbit).
2. Antenna mass and size, both space and terrestrial assets.
3. Atmospheric transit of beamed power.
4. Routine Launch operations to space at low cost: 4000 to 8000 1-GW satellites needed.

Steps involved in SSP are:
Collection and concentration of sunlight – need large area.
Conversion to DC/AC electric power – many options.
Conversion to beamed power & transmission to receivers.
Reception & conversion.

We add one more as a critical interim need and source of support for SSP:
Power Exchange Between Terrestrial Entities

Critical step on the road to SSP: Demonstration of wireless transfer of power that is safe, efficient and cost-effective.
Experiment Components

5-7 nations/space agencies as potential partners for these first experiments: USA, Japan, Russia, Europe, China, India, Australia

Two space assets:
1. ISS ~ 400 km orbit height, 51.6 degree inclination (Cargo launcher + deployment)

2. A multinational waveguide/reflector satellite. 2000 km orbit height, sun-synchronous orbit. (Polar launch vehicle)

Terrestrial assets:
1. Ground receivers (~ 150m diameter) for millimeter wave reception.
2. Transmitters for millimeter wave power, to beam to satellites.
3. Launch, command, data acquisition and control facilities.
4. Sensor arrays and data systems to study atmospheric absorption and scattering of millimeter waves.
Orbits

ISS: 390 to 405 km height; ~ 52 degrees inclination
Waveguide Satellite: ~ 2000 km sun-synchronous orbit (close to polar)
Technical / Architecture Departures
(Why we believe that SSP can be made viable)

• Millimeter Wave frequencies (94, 170, 220 GHz) reduce antenna size. R&D need to improve efficiency and specific power of mm waves.

• Dynamic beaming from 2000 km orbits reduces antenna size. Dynamic pointing corrections and fast switching technologies well in hand; Smart grid advances enable transient power transfer and on-grid storage.

• Terrestrial plants as both transmitters and receivers; provides startup and market with low risk, well before the first major SSP Generator satellite launch.

• Space assets as generators, transmitters, receivers and waveguide/reflectors

• Strong potential to break through in specific power for large SSP plants using primary Brayton cycle converters rather than PV arrays. (Jet engines achieve well over 10 kW/kg)
1. Science Objectives

• Millimeter Wave Propagation Through Atmosphere. Present public-domain data are mostly from astronomical observatories (high altitude). Conduct high-resolution sweep of frequency space around the transmission windows.
  
  - Sources of losses
  - Water effects
  - Oxygen and nitrogen absorption
  - Ionospheric effects
  - Magnetosphere effects
  - Climate data
  - Nonlinear interaction between beam and atmosphere
  - Identify “best” frequencies
  - Health and safety (using millimeter waves)

• Conversion to and from Millimeter Waves
  
  - Direct conversion/ optical antenna options
  - Electro-optics
2. Technology Demonstrations

- Low-mass antenna design for millimeter waves;
- Low-mass, resonant millimeter waveguides;
- Conversion from solar-generated DC to millimeter waves;
- Dynamic pointing accuracy, with adaptive refinement;
- Beam capture efficiency/safety;
- Conversion from millimeter waves to useful terrestrial power;
- Power grid aspects of dynamic beaming;
- Capture of terrestrial power at spacecraft;
- Reflection/ waveguiding of terrestrial power through spacecraft to in-space target;
- Retail beaming;
- Aerial platforms for transmission and capture;
- Waveguide tethers; and
- Beamed propulsion
3. Public policy exercise

- Visualization and acceptance of orbiting power stations;
- Public/private funding of power stations;
- Acceptance of retail power beaming;
- Pricing of terrestrial and space-generated power;
- Power grid integration of dynamic power beaming
- Multinational agreements on technology sharing;
- Multinational collaboration in spacecraft construction, deployment and operations; and
- Multinational collaboration in power exchange
4. Public education objectives

1. Why?
2. How?
3. What can be done today?
4. Why we must start today to reach success in 15 years, and
5. What is the realistic risk? What are the Payoffs?
5. Build Momentum

A visible, functioning multinational demonstration working for several years generating useful science, technology and measurable progress towards full implementation of Space-based Solar Power.
Prior Proposals

Potter/Mankins et al, 2008: MSC-1A: Boeing/NASA Near Term Demonstration 100 kWe Power Plug Satellite

- 120 kWe array derived from ISS 61.5 kW array + advanced PV
- 30% converter LEDs.
- 36kW transmitted as light beam.
- Beam pointing by reflectors.

Potter, ISDC 2011:
Proposal for 94GHz 10 kWe converter on ISS, with receivers in Goldstone, AZ Florida, Australia. Dynamic beam pointing.

Our proposal draws on these. It limits space-based power generation to what is already done on the ISS. Expands mission to include long-duration science experiment on atmospheric beaming and interactions using millimeter waves. Also adds Earth-to-Space beaming and Space-Space beaming technology demonstrations.
ISS Experiment

- 6.25kW DC standard ISS power module

- 5 kW available for conversion to mmwave.

- 3 converters: 94 GHz, 170 GHz, 220 GHz.

- Single 10m diameter external transmitting antenna, intermeshing 3 frequencies.

- Broadband vs. narrowband waveguides.

- Resonant waveguides vs. reflectors.

- Safety systems to verify beam lock on receiver.

- Measurements of conversion efficiency, transmission efficiency, heating load.

- 150 meter ground receivers; Aerial Platforms as receiver-distributors.
Multinational WaveguideSat Experiment

• 2000 km sun-synchronous orbit.
• 4000 kg waveguide satellite, suitable for polar launcher
• Beam from terrestrial stations, measure reception, spillover, heating
• Reflector / waveguide performance, efficiency
• Orbit-correction propulsion
• Component survival and performance under cyclic, intense power loading
• Aerial Platforms as Transmitters
# Power Transfer Windows

<table>
<thead>
<tr>
<th>Satellite</th>
<th>Ground Facility</th>
<th>Mean Beaming Time (s)</th>
<th>Avg. Occurrences Per Day</th>
</tr>
</thead>
<tbody>
<tr>
<td>ISS</td>
<td>Goldstone</td>
<td>84</td>
<td>0.98</td>
</tr>
<tr>
<td>ISS</td>
<td>Central India</td>
<td>81</td>
<td>0.84</td>
</tr>
<tr>
<td>2000km sun-sync</td>
<td>Goldstone</td>
<td>404</td>
<td>2.10</td>
</tr>
<tr>
<td>2000km sun-sync</td>
<td>Central India</td>
<td>401</td>
<td>1.89</td>
</tr>
</tbody>
</table>
Roadmap Beyond

Design the first operational Waveguide Satellite;

Design converter satellites;

Design the first Waveguide satellite constellation for a Space Power Grid; and

Launch the first SSP generator satellites.
SSP Viability Projection

\[ k = 25000 P \eta s/c \]

- **P**: selling price, $/kWhe
- **Y**: efficiency of transmission to the ground
- **s**: kWe generated in space per kg mass in orbit
- **c**: launch cost to LEO in $/kg

### Specific Power $S$, kWe/kg in orbit

- **PV, GEO 5.8GHz**
- **PV, mmWave SPG 220GHz**
- **Direct Conversion, mmWave SPG**
- **InCA, mm Wave, SPG**
THANK YOU! DISCUSSION?
The Space Power Grid Approach

- Exploit large geographical, daily and seasonal fluctuations in power cost.
- Beam to other satellites.
- Retail delivery (SPS2000).

Use space-based infrastructure to boost terrestrial “green” energy production from land and sea; argument for public support.

Full Space Solar Power (very large collectors in high orbit) will add gradually to revenue-generating infrastructure.
Effective Antenna Diameter for 84 percent beam capture
SPG millimeter wave antennae are designed to allow 96 percent capture and will be roughly 3 times these diameters.