Criteria for Comparing Power Beaming Demonstrations

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SPECTRUM ALLOCATION IS A CRITICAL PREREQUISITE FOR MICROWAVE POWER BEAMING FOR SPACE SOLAR POWER
Why Power Beaming?

Comparatively easy place to get energy

Power beaming

Hard or expensive place to get energy

Long separation ill-suited for a physical connection
For Activities Needing Energy at a Given Time & Location

1. Activity needs energy
2. Yes: Sustainable while local source available (stored or harvested)
3. No: Consider wireless energy delivery
4. Energy available locally?
   - Yes: Sustainable while stored energy delivered via mass (fuel, batteries, etc.)
   - No: Consider wireless energy delivery
5. Stored energy delivery?
   - Yes: Sustainable while energy delivered via connection (wire, fiber, waveguide, etc.)
   - No: Consider wireless energy delivery
6. By direct connection?
   - Yes: Sustainable while energy delivered via connection (wire, fiber, waveguide, etc.)
   - No: Consider wireless energy delivery
Power Beaming Block Diagram

Input Source → Power Conversion → Transmit Aperture → Receive Aperture → Power Conversion → Output Load

Transmission Media
Electromagnetic Spectrum Regions of Interest for Power Beaming

- Gamma Rays, X-Rays and Ultraviolet Light blocked by the upper atmosphere (best observed from space).
- Visible Light observable from Earth, with some atmospheric distortion.
- Most of the Infrared spectrum absorbed by atmospheric gasses (best observed from space).
- Radio Waves observable from Earth.
- Long-wavelength Radio Waves blocked.

Figure adapted from
https://img1.wikia.nocookie.net/__cb20071104233556/psychology/images/8/83/Atmospheric_electromagnetic_transmittance_or_opacity.jpg
ATTENUATION OF EM WAVES BY THE ATMOSPHERE

Scattering Losses

Absorption losses occur below the "scattering loss" line.

Figure from https://upload.wikimedia.org/wikipedia/commons/7/78/Atmosph%C3%A4rische_Absorption.png
Power Beaming Applications

Figure credit: LaserMotive
Power Beaming for Drones?

7-Eleven completes ‘historic’ Slurpee delivery via drone, beating Amazon to the punch

Could Drones Help Save People In Cardiac Arrest?

Could Drones Help Save People In Cardiac Arrest?

http://mydronelab.com/blog/delivery-drones.html


Selected Microwave Power Beaming Demonstrations

JPL-Raytheon Goldstone, 34 kW, 1.6 km (1975)

MILAX Kobe University (1992)

Dickinson and Brown, 54% (1975)

Aerostat phone charging Kyoto U. (2009)

Mitsubishi Electric 5.8 GHz 55m (2015)
Selected Laser Power Beaming Demonstrations

EADS Astrium tracking laser to power rover (2003)

Kinki Univ. & Hamamatsu Photonics Inc. laser power to small helicopter (2007)


LaserMotive outdoor laser power to Stalker UAV (2012)
Inclusion Criteria for Demonstrations

• Demonstrated end-to-end transmission efficiency of at least 1%

• Spanned a distance of at least 1 m  (where 1 m is beyond the reactive near field of the transmitter)

• Met the conditions above for at least 1 minute
This Rules Out (Typically) ...

- Communication links
  - Goal is to keep carrier above noise
- Directed energy
  - Goal is disrupting, disabling, or destroying a target
- Energy harvesting
  - Goal is exploiting ambient resources
- Radars
  - Goal is capturing reflected energy for analysis
- Medical devices, industrial equipment, microwave ovens, etc.
- Systems within the reactive near field
  - Capacitive and inductive resonance
Figures of Merit for Operational Power Beaming Systems

• Range (m)
  – Generally want to maximize ↑

• Power delivered (W)
  – Generally want to maximize ↑

• Efficiency (%)
  – Generally want to maximize ↑

• Cost ($/W, $/W·m, $/kWh)
  – Generally want to minimize ↓

• Safety (# birds fried)
  – Generally want to minimize ↓

Source: https://youtu.be/0WYu25SZKIY?t=36m
## Metrics & Data for Power Beaming Demos & Systems

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Date</td>
<td>The date the demonstration occurred. For multi-day demonstrations, the first day of operation.</td>
</tr>
<tr>
<td>Location</td>
<td>The location the demonstration occurred.</td>
</tr>
<tr>
<td>Title</td>
<td>A short, descriptive title to distinguish the demonstration from others.</td>
</tr>
<tr>
<td>f (Hz)</td>
<td>The principal center frequency of operation for the demonstration.</td>
</tr>
<tr>
<td>λ (m)</td>
<td>The wavelength corresponding to the frequency of operation.</td>
</tr>
<tr>
<td>FWHM (Hz)</td>
<td>The full width at half maximum of the transmitter bandwidth.</td>
</tr>
<tr>
<td>Tx ⌀ (m)</td>
<td>The largest dimension of the transmitter aperture, typically the diameter.</td>
</tr>
<tr>
<td>Tx mass (kg)</td>
<td>The mass of the transmitter, including power conversion elements and the transmit aperture.</td>
</tr>
<tr>
<td>Tx vol (m³)</td>
<td>The volume of the transmitter, including power conversion elements and the transmit aperture.</td>
</tr>
<tr>
<td>Rx ⌀ (m)</td>
<td>The largest dimension of the receiver aperture, typically the diameter.</td>
</tr>
<tr>
<td>Rx mass (kg)</td>
<td>The mass of the receiver, including power conversion elements and the transmit aperture.</td>
</tr>
<tr>
<td>Rx vol (m³)</td>
<td>The volume of the receiver, including power conversion elements and the transmit aperture.</td>
</tr>
<tr>
<td>Range (m)</td>
<td>The distance between the transmit and receive apertures.</td>
</tr>
<tr>
<td>Max BE</td>
<td>The maximum beam efficiency theoretically achievable from the aperture areas, range, and operating frequency.</td>
</tr>
<tr>
<td>Tx input (W)</td>
<td>The input source power to the transmitter.</td>
</tr>
<tr>
<td>Tx power (W)</td>
<td>The power output of the transmitter at the frequency of operation.</td>
</tr>
<tr>
<td>Tx eff</td>
<td>The percentage of input power that is transmitted.</td>
</tr>
<tr>
<td>Tx pk (W/m²)</td>
<td>The peak power density on the transmit aperture.</td>
</tr>
<tr>
<td>Beam pk (W/m²)</td>
<td>The peak power density along the beam's path.</td>
</tr>
<tr>
<td>Rx pk (W/m²)</td>
<td>The peak power density at the receive aperture.</td>
</tr>
<tr>
<td>Rx power (W)</td>
<td>The power incident on the receive aperture.</td>
</tr>
<tr>
<td>Rx output (W)</td>
<td>The average power from the receiver to the output load over the duration of the demonstration.</td>
</tr>
<tr>
<td>Rx eff</td>
<td>The percentage of incident on the receive aperture that is sent to the output load.</td>
</tr>
<tr>
<td>End-to-end eff</td>
<td>The percentage of power from the input source that is delivered to the output load.</td>
</tr>
<tr>
<td>Duration (s)</td>
<td>The duration over which power was provided to the output load.</td>
</tr>
<tr>
<td>Beam steering</td>
<td>Beam steering implemented, such as: none, electronic closed or open loop, mechanical closed or open loop</td>
</tr>
<tr>
<td>Safe [Y/N]</td>
<td>To answer &quot;Y&quot;, the demo either did not exceed the applicable power density safety limits (IEEE, OSHA, ICNIRP, etc.), or an interlock system was implemented and tested to prevent harm to personnel, animals, or property.</td>
</tr>
<tr>
<td>Cost ($)</td>
<td>Cost of the demonstration in then-year U.S. dollars.</td>
</tr>
<tr>
<td>W cost ($/W)</td>
<td>Cost per watt delivered to to output load</td>
</tr>
<tr>
<td>Tag</td>
<td>The year the demonstration was performed suffixed with a letter to allow tagging of the demonstration on plots</td>
</tr>
<tr>
<td>Notes</td>
<td>Notes and aspects of interest related to the demonstration.</td>
</tr>
<tr>
<td>Reference</td>
<td>Primary source for data.</td>
</tr>
<tr>
<td>Add'l References</td>
<td>Additional data sources</td>
</tr>
</tbody>
</table>
The Power Beaming Leader Board

<table>
<thead>
<tr>
<th>Category</th>
<th>Record</th>
<th>Year</th>
<th>Demonstration</th>
</tr>
</thead>
<tbody>
<tr>
<td>Longest Range</td>
<td>1.55 km</td>
<td>1975</td>
<td>JPL-Raytheon Goldstone*†</td>
</tr>
<tr>
<td>Most Power Delivered</td>
<td>34 kW</td>
<td>1975</td>
<td>JPL-Raytheon Goldstone*</td>
</tr>
<tr>
<td>Highest Efficiency</td>
<td>54%</td>
<td>1975</td>
<td>Brown &amp; Dickinson*</td>
</tr>
</tbody>
</table>

* it is not completely clear if these demos meet the 1 minute criterion
† this distance may have been tied or slightly exceeded by one executed by Sichuan University in 2016, albeit at lower power.
Ground Based Wireless & Wired Power Transmission Cost Comparison

Conclusion

• Clear, concise criteria were presented for what constitutes a power beaming demonstration:
  > 1% end-to-end efficiency
  > 1 meter distance
  > 1 minute demonstrated

• Key figures of merit are range, power delivered, efficiency, cost, and safety

• It’s time to break some records
Thank You for Your Attention
Your Feedback is Most Welcome
Backup
Power Beaming Solves The Critical Problem Of Getting Energy Where It Is Needed Most
Potential for Dual Use with Non-lethal or Directed Energy Assets

- Active Denial System (mm-wave)
- Laser Weapons Systems (LaWS) on the U.S.S. Ponce
Key Points

1. Power beaming is an emerging disruptive technology

2. There are important tradeoffs in system implementation between:
   – Safety and power density
   – Wavelength and aperture size

3. Recent breakthroughs in component technologies have increased system feasibility

4. The research and industrial base is eager to develop and transition capabilities in this area to operations
Summary

• Power beaming is an emerging disruptive technology

• Breakthroughs in component technologies (fiber lasers, low-power energy harvesting, etc.) now make a variety of potential systems attractive for various applications

• The research and industrial base is eager to transition capabilities in this area to operations
NRL Sunlight-to-Microwave Converters

- Completed and tested in space-like conditions the most efficient, highest specific power sandwich conversion modules to date
  - 8% & 7%, ~4x previous record
  - 4.5 W/kg & 5.8 W/kg
- Demonstrated and tested a novel new sandwich module design that addresses thermal concerns
- Provided a meaningful empirical basis for space solar economic studies
The Underlying Physics

The takeaway: Shorter wavelengths mean smaller transmitter and receiver areas for higher beam efficiency, but also more concentrated power.

Research and Industry Activity

• Research activity for power beaming:
  – IEEE Wireless Power Conference and Wireless Power Transfer journal
  – U.S. Government: NRL, ONR, CERDEC, AFRL, DARPA, SPAWAR, etc.
  – Int’l Universities: Kyoto U., Kobe U., many others in Japan and China

• Industry activity for power beaming:
  – Primes: Raytheon (long history, newly formed internal effort), Northrop Grumman
  – Startups: Lasermotive, Lighthouse DEV, Van Wynn (Canadian)

• non-U.S. government activity: Japan, China, UAE, EU
• A lot of crossover with directed energy (DE)
Power Beaming Technologies

BOLD indicates an area with significant recent advances

• Laser (800nm, 1µm, 1.5µm, etc)
  – Transmitter: fiber laser, diode laser, etc.
  – Receiver: PV, TPV, heat engine

• mm-wave (~94 GHz)
  – Transmitter: gyrotron, solid state, etc.
  – Receiver: rectenna, heat engine

• Microwave (~2 GHz-35 GHz)
  – Transmitter: vacuum electronics, solid state
  – Receiver: rectenna

• Supporting tech
  – high altitude vehicles, aerostats, etc.
Potential for International Collaboration

- Japan – Ongoing research conducted by the Japanese Space Agency JAXA and affiliated organizations (Japan Space Systems) and Universities
- China – Many government and University research efforts across a broad swath of topics
- India – Persistent high-level government and popular interest, prospective startups
- European Union – Advanced concepts work ongoing through ESA and Universities, aerospace companies
- United Arab Emirates / Dubai – Focused interest on the possibility of doing a space or terrestrial hardware demonstration for Expo 2020
- Canada – Interest on the part of senior government officials and the nonprofit Space Canada
- South Korea – National power company interest in wireless power and future clean energy sources
Power Beaming Applications: Autonomous and Remotely Operated Systems

**Increased:**
- Dwell time
- Payload capacity
- Operational flexibility

**Specific applications:**
- Intelligence, Surveillance, Reconnaissance
- Communications
- Off-board countermeasures
- Unattended ground sensors/buoys
NRL Laser Power Beaming Demonstration

Total weight < 2kg
PV output 160-190 W
Voltage 11 V dc
Example Platform: Zephyr HALE (High Altitude, Long Endurance) UAV

- Limited payload capacity
- Can fly overnight using stored solar, but with operating constraints
- Power beaming could provide day or night recharging to increase payload capacity and operational flexibility in terms of range and duration
Power Beaming Applications:
Forward Power Distribution Network

Increased:
- Power distribution flexibility
- Resilience

Specific applications:
- FOB and COP energy resupply
- Ship-to-shore energy provision
- Unattended sensors

NRL 5kW 3.2 km Laser Transmission Demo
Space-to-space Power Beaming

- Power Generating & Transmission Satellites in High-illumination Orbit
  - Collect/convert solar energy into electrical energy
  - Store electrical energy in on-board batteries as needed
  - Wirelessly transmit electrical energy to other orbits, such as Low-Earth-Orbit (LEO) and Very Low Earth Orbit (VLEO), others
  - Can also potentially be utilized as data relay