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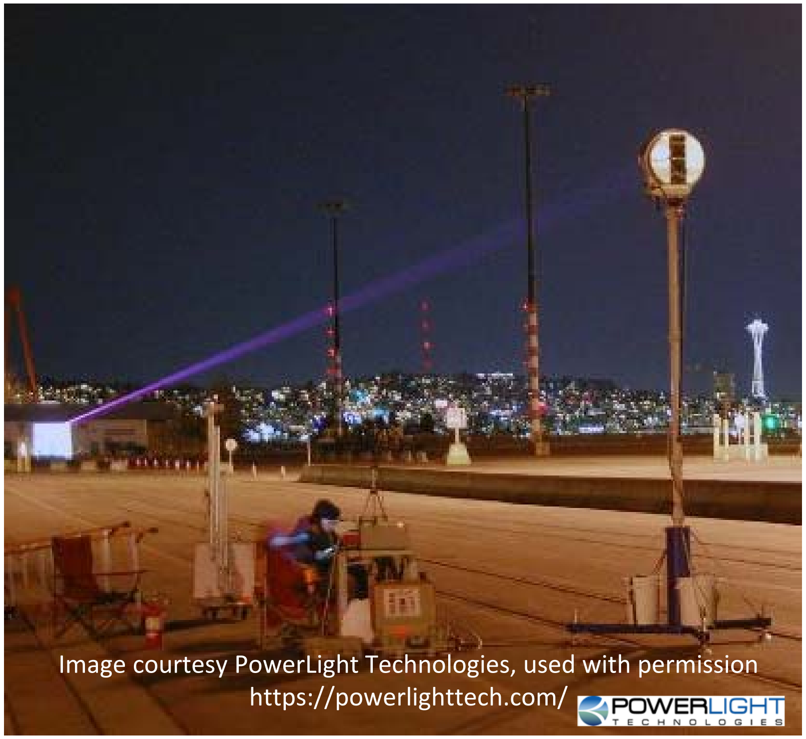

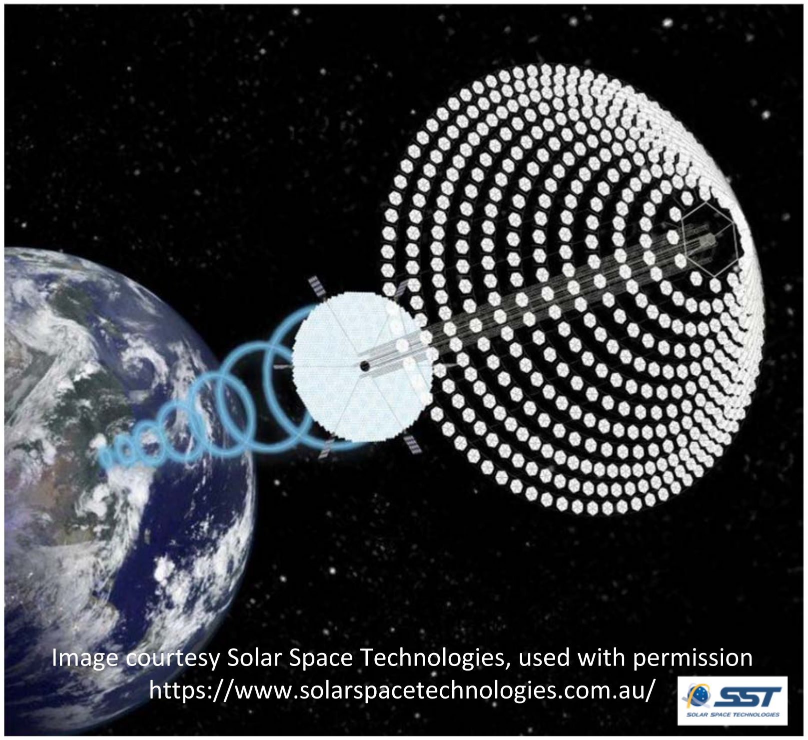

Power Beaming and Space Solar

Paul Jaffe, PhD

202-767-6616

Paul.Jaffe@nrl.navy.mil

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What is Power Beaming?

Power Beaming is delivering meaningful amounts of energy without moving or employing mass between the transmitter and receiver

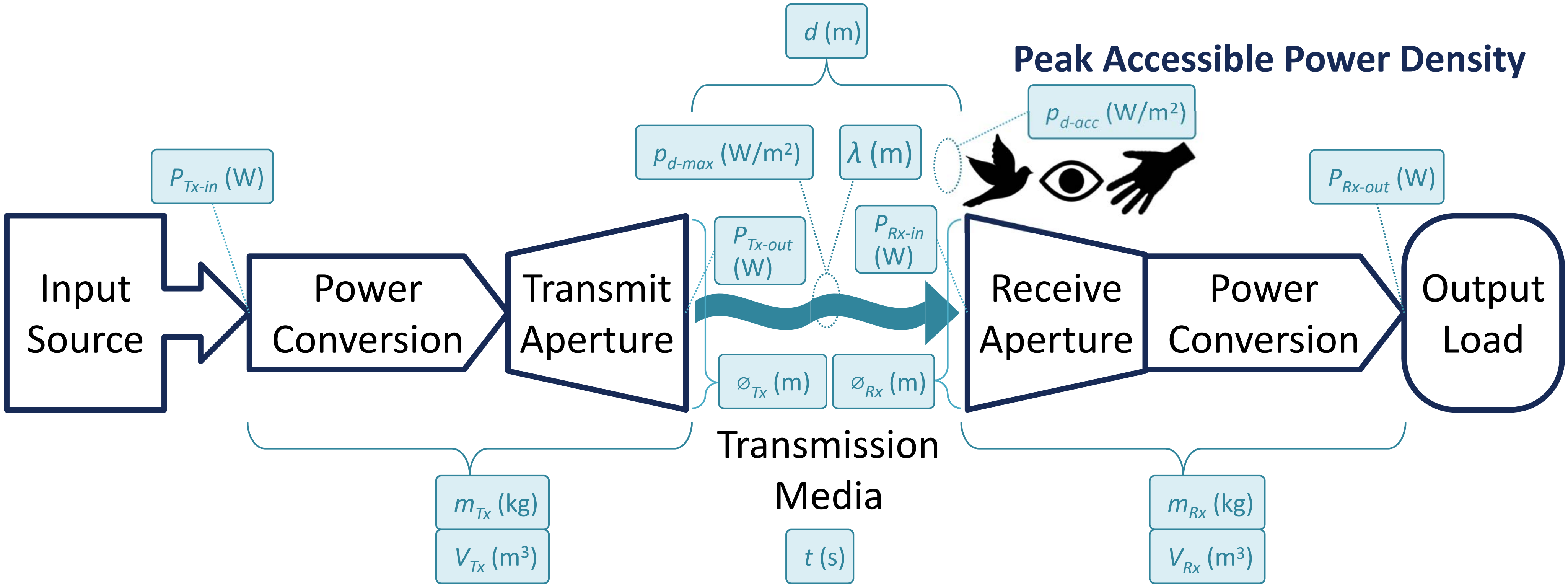
Comparatively easy place to get energy

Power beaming

Hard or expensive place to get energy

Separation ill-suited for a physical connection

Critical Power Beaming Measurements



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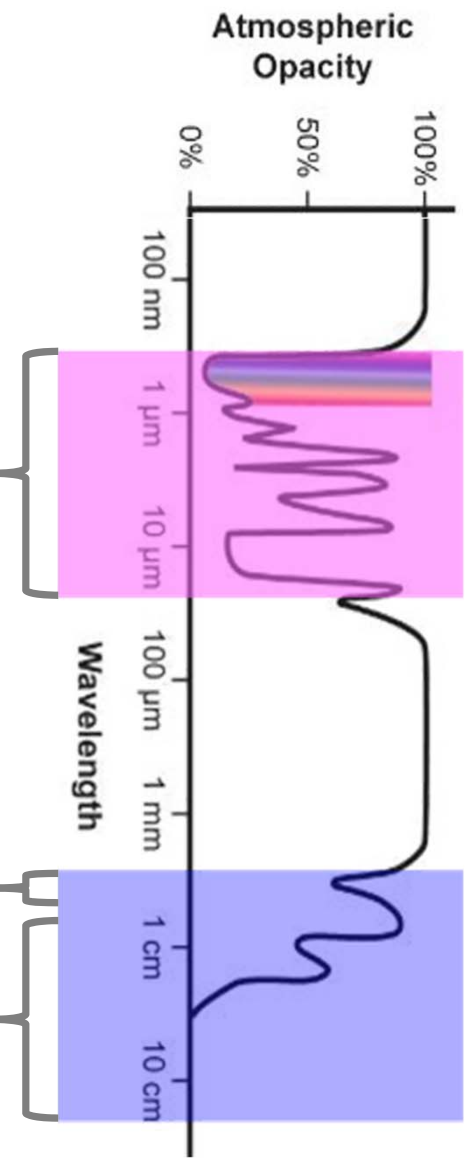
Power Beaming Modalities

- 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



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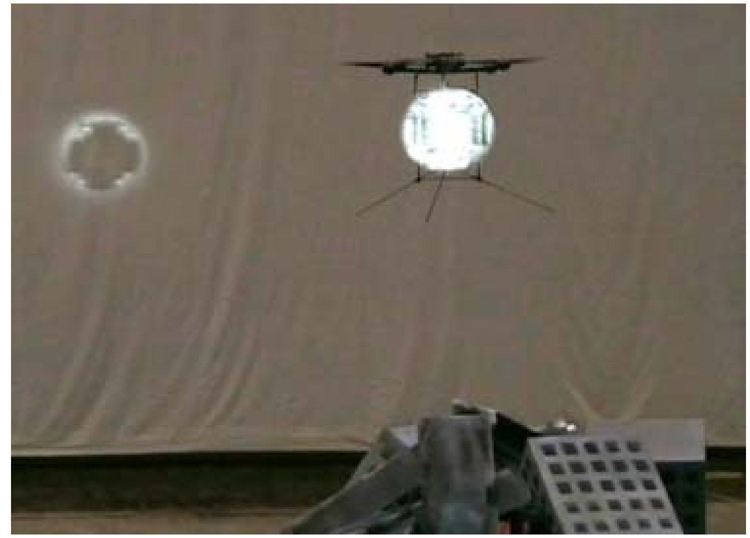
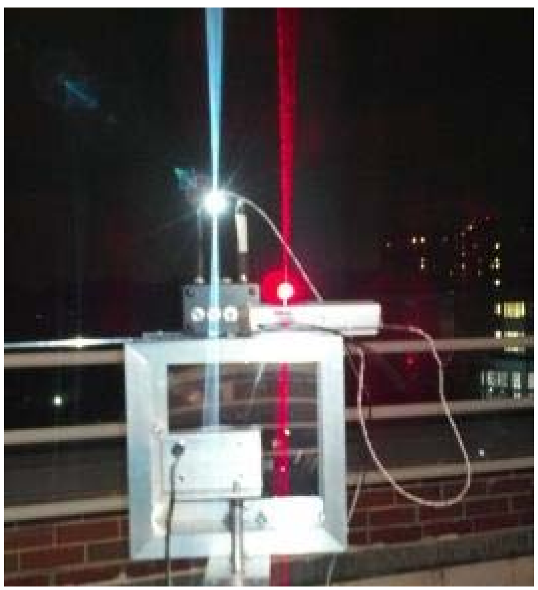
Selected Laser Power Beaming Demos

EADS Astrium tracking laser to power rover (2003)



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

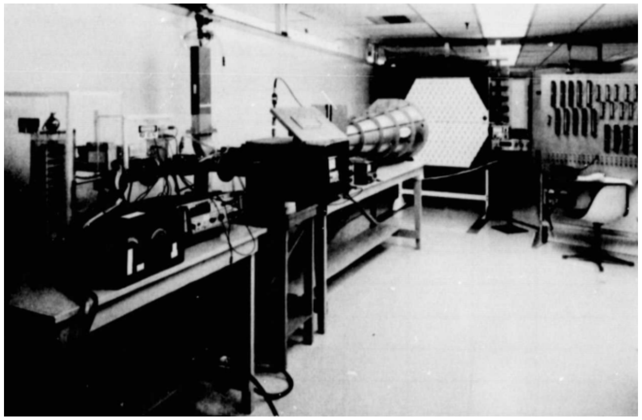


Lighthouse DEV Eye-safe laser demo (2012)
http://www.bbc.co.uk/programmes/p00yjt99 5:40

LaserMotive outdoor laser power to UAV (2012)

PowerLight point-to-point power link (2019)

Selected Microwave Power Beaming Demos



Dickinson and Brown, 54% (1975)

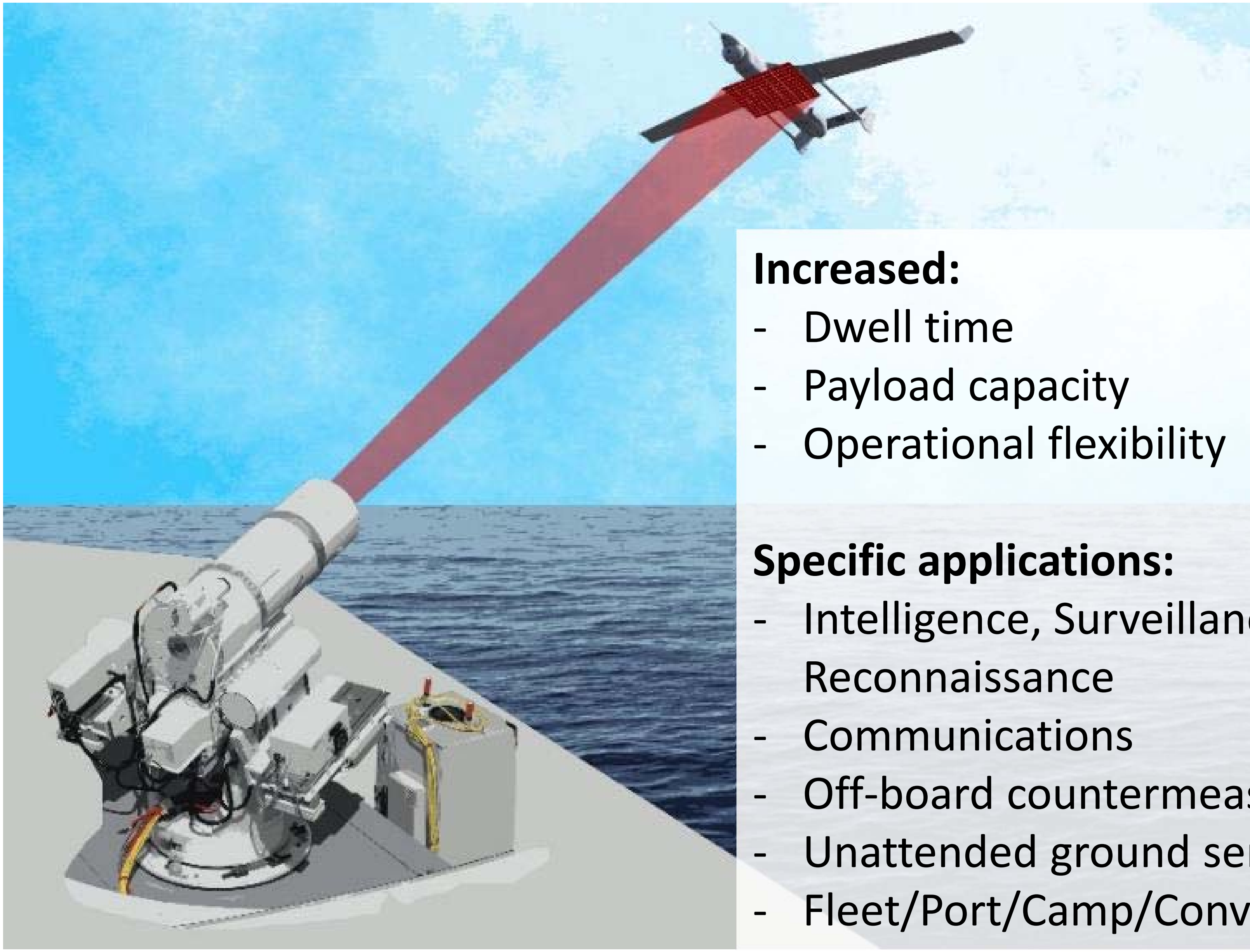
JPL-Raytheon Goldstone, 34 kW, 1.6 km (1975)

MILAX Kobe University (1992)

Aerostat phone charging Kyoto U. (2009)

Mitsubishi Electric 5.8 GHz 55m (2015)

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
- Fleet/Port/Camp/Convoy Protection

Example Platform: High Altitude, Long Endurance (HALE) UAV

- Limited payload capacity
- Can fly overnight using stored solar, but with operating constraints
- Power beaming could provide day/night recharging, increasing payload capacity, operational flexibility, range and duration

Power Beaming Applications: Remote Installation Power Distribution Network

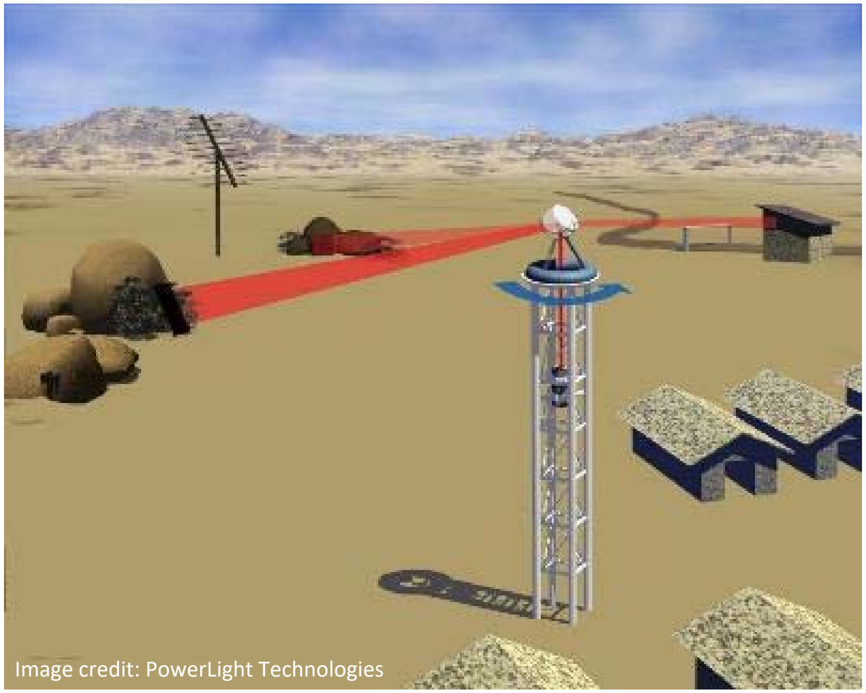
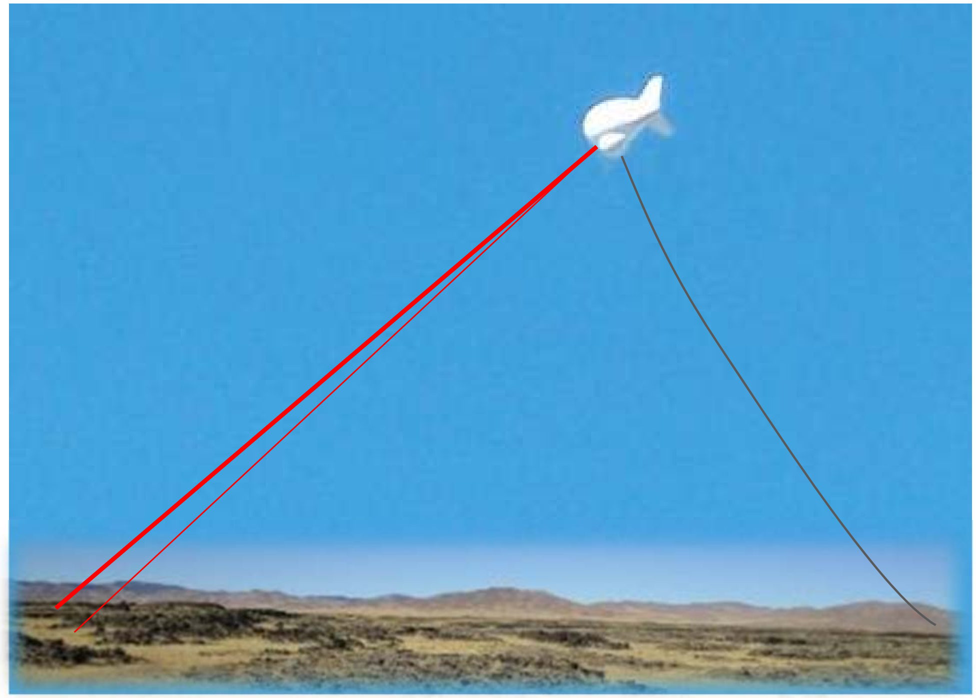
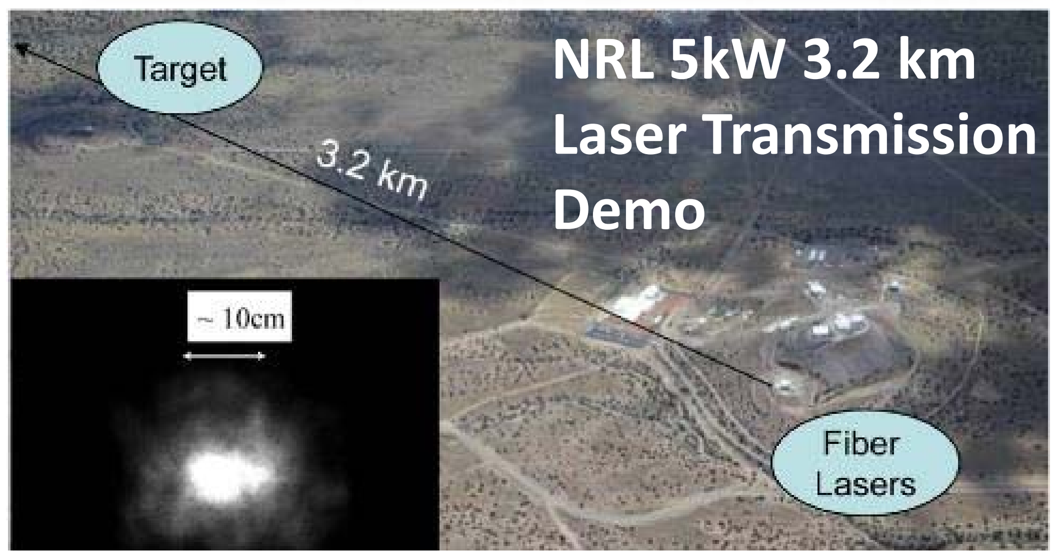


Image credit: PowerLight Technologies





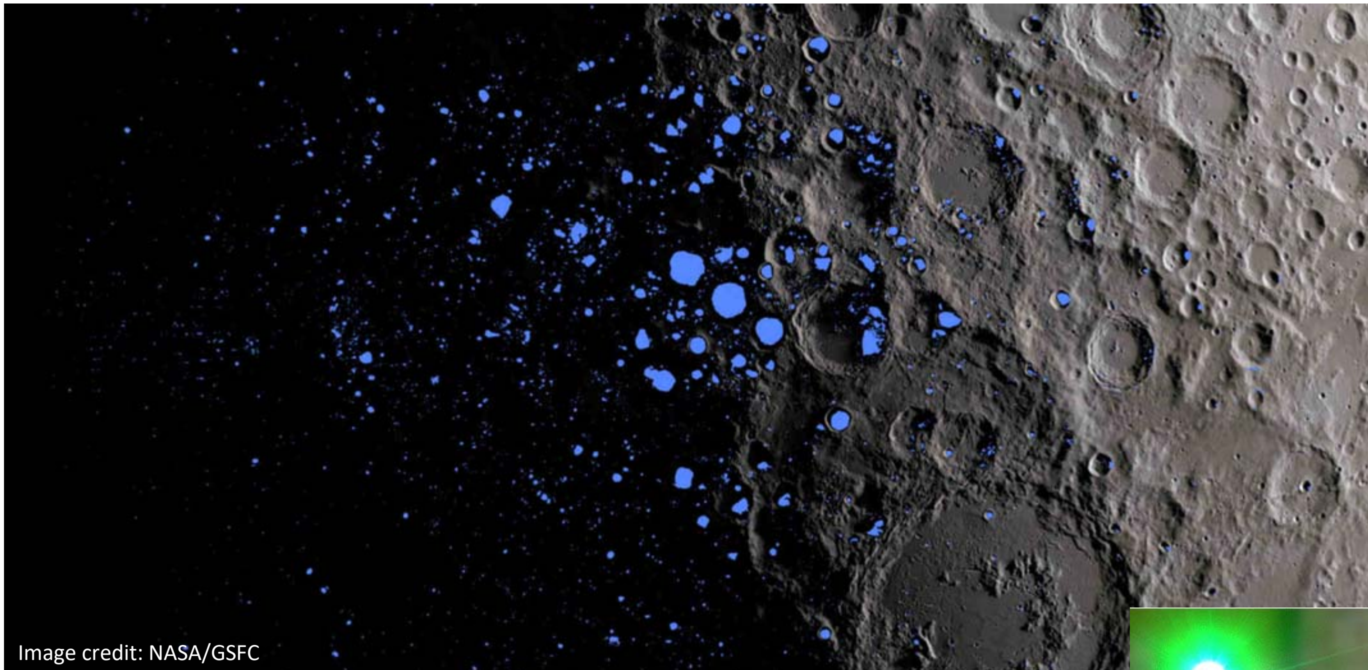
Increased:

- Power distribution flexibility
- Resilience

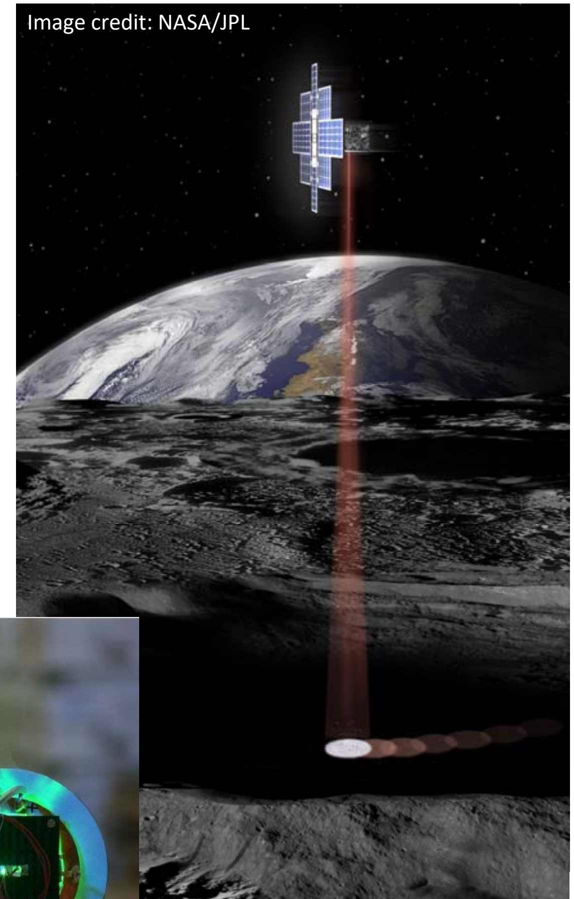
Specific applications:

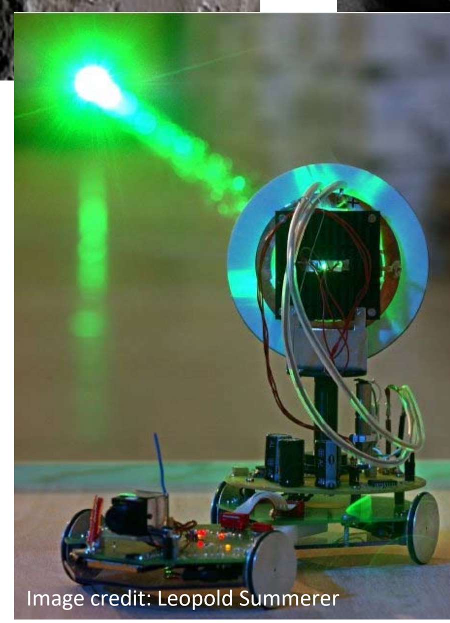
- Outpost energy resupply
- Ship-to-shore energy provision
- Unattended sensors

Power Beaming Applications: Planetary Body Power Distribution Network



Blue regions are permanently shadowed





Increased:

- Power distribution flexibility
- Resilience

Specific applications:

- Permanently shadowed lunar craters
- Contending with two-week lunar night
- Asteroid prospecting

Power TRansmitted Over Laser (PTROL) Demo 2

Demo in Seattle, WA, April 2019

Demo at NSWC Carderock, Bethesda, MD, May 2019

Beam is infrared

It is difficult to detect in daylight and by "garden variety" night vision gear

https://youtu.be/Xb9THqrXd4I

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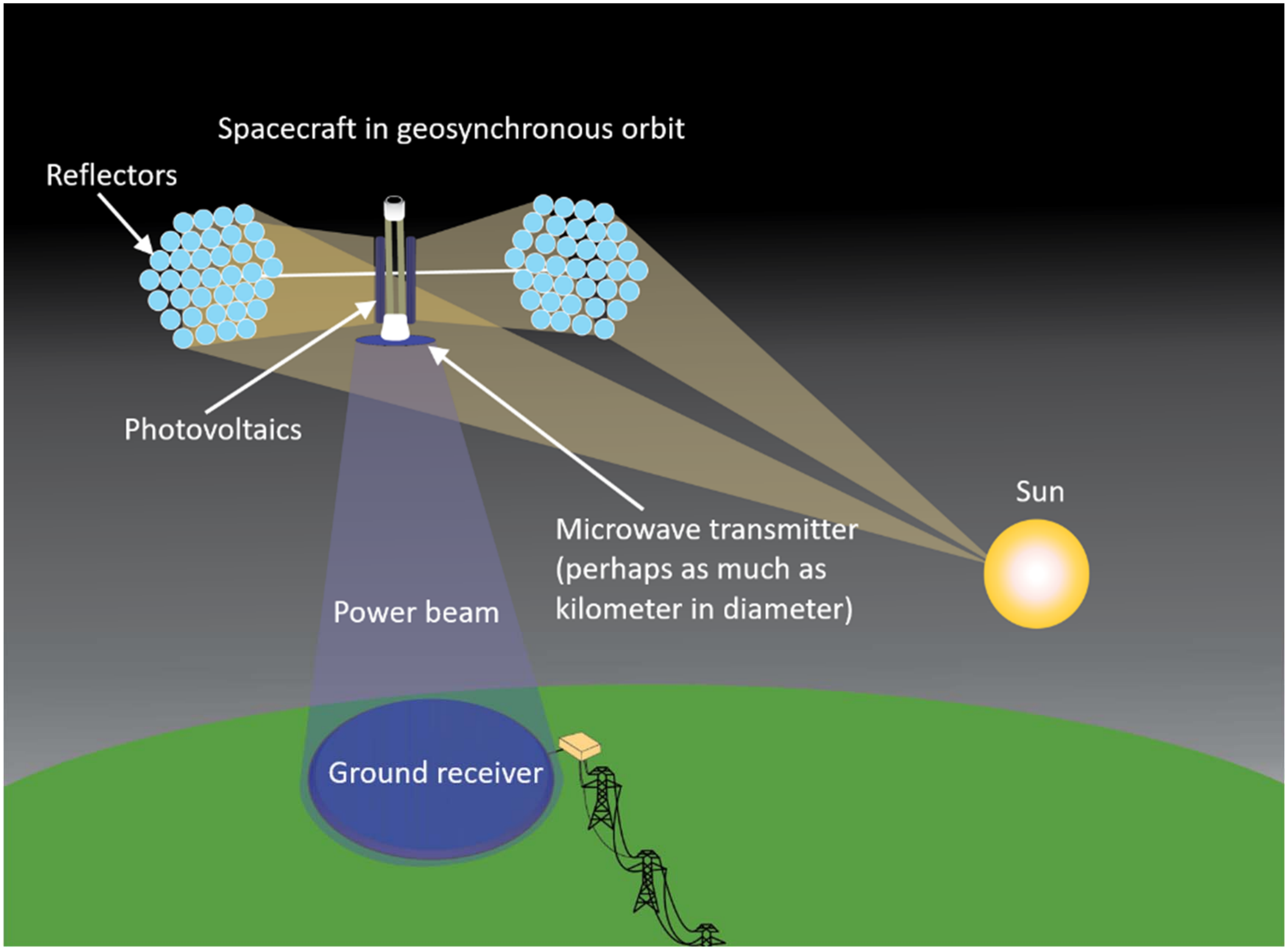
Power Beaming Summary

- Power beaming is an emerging disruptive technology
- Recent breakthroughs make power beaming attractive for some applications
- The research and industrial base is eager to transition capabilities in this area to operations

"being able to beam [energy] from spot to spot in the same way that we use copper wire … that will be very critical." - Dr. Michael D. Griffin, USDR&E, 06 September 2018

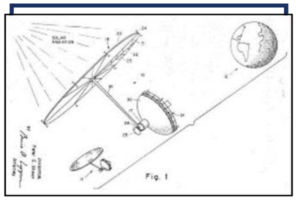
What is Space Solar?

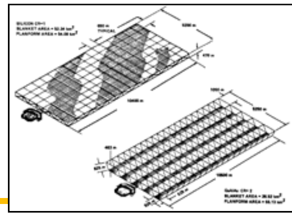
Space Solar is the collection of solar energy in space and its wireless transmission for use on earth



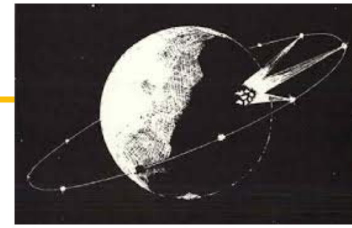
(This depiction is merely one of many proposed implementations)

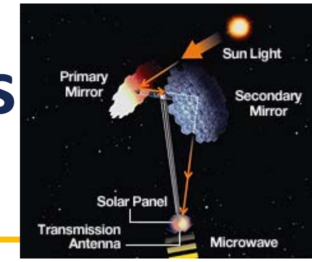
Some proposed implementations


Peter Glaser GEO concept, circa 1968

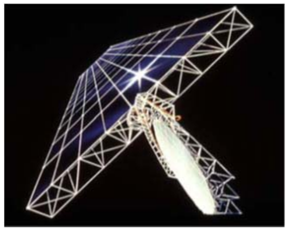

NASA/DOE SPS Reference System, circa 1978

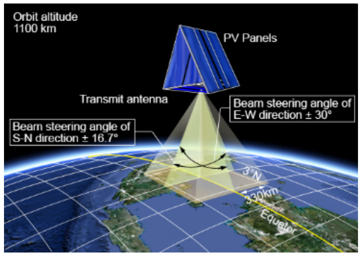

Perpendicular to Orbital Plane, circa 1973


Krafft Ehricke Soletta Space Mirrors, circa 1978

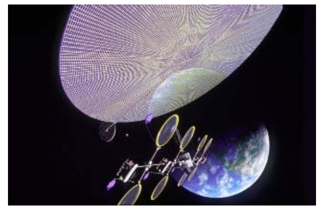


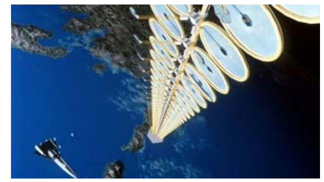
NASA/DOE Microwave sandwich concept, circa 1980

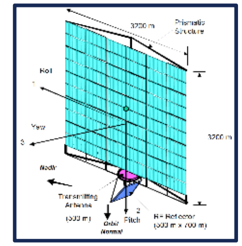

NASA Reference Design, circa 1981

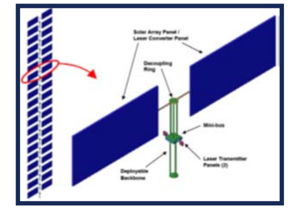


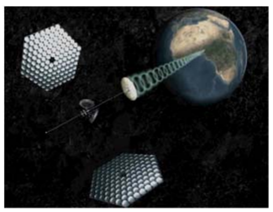
Japanese SPS-2000 LEO concept, circa 1994

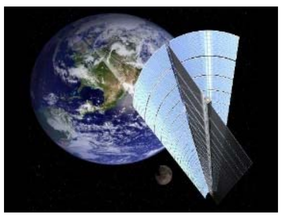

SolarDisc, circa 1997


SunTower, circa 1997

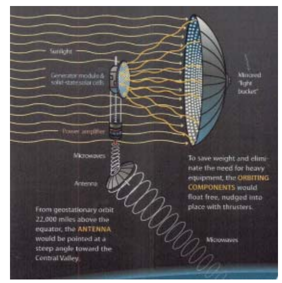

Abacus, circa 2001

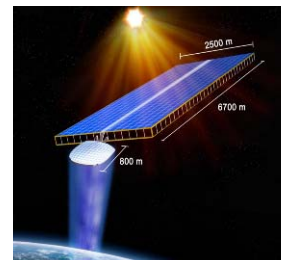

Aerospace Corp. Laser Concept, circa 2002


Modular Symmetrical Concentrator, circa 2007

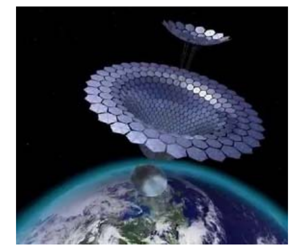

JAXA modular laser, circa 2008

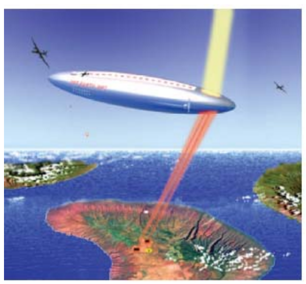

EADS Astrium laser concept, circa 2011

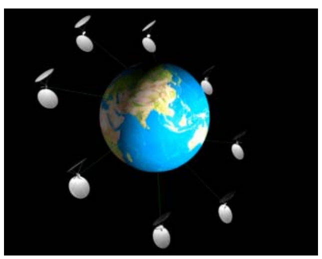

Solaren, circa 2010

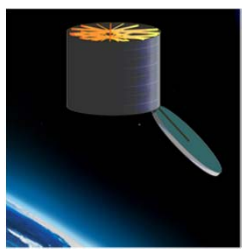


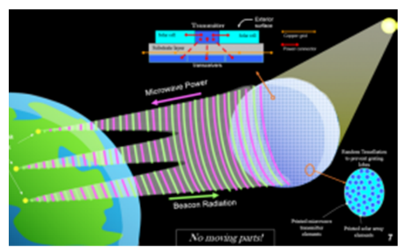
SolarHigh, circa 2012


SPS-ALPHA, circa 2013

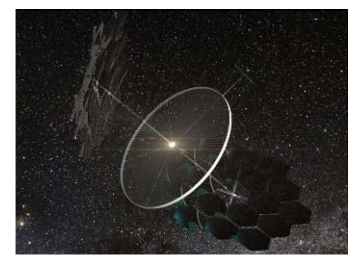

Dickinson Laser to High-Altitude Platform to Microwave, circa 2013

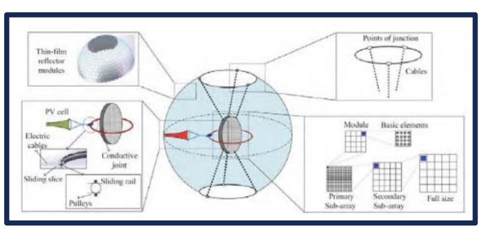

Sun Synchronous Orbit Concentrating PV, circa 2014

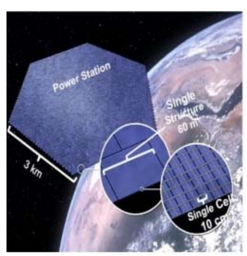

Tin Can SPS, circa 2014


Hyland Power Star, circa 2014

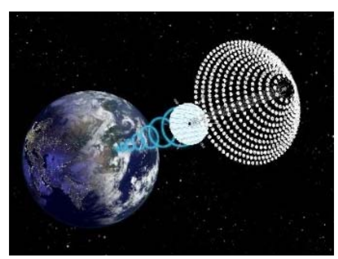

China Academy of Space Technology (CAST) Multi-Rotary Joints SPS, circa 2015


Team Sunflower Thermal Power Satellite, circa 2015


SPS-OMEGA, Xidian University, circa 2014



Caltech/NG SSPI, circa 2015


SPS-ALPHA MKII, circa 2016


CASSIOPeiA, circa 2017

Etc….

Subsystems of a Solar Power Satellite System

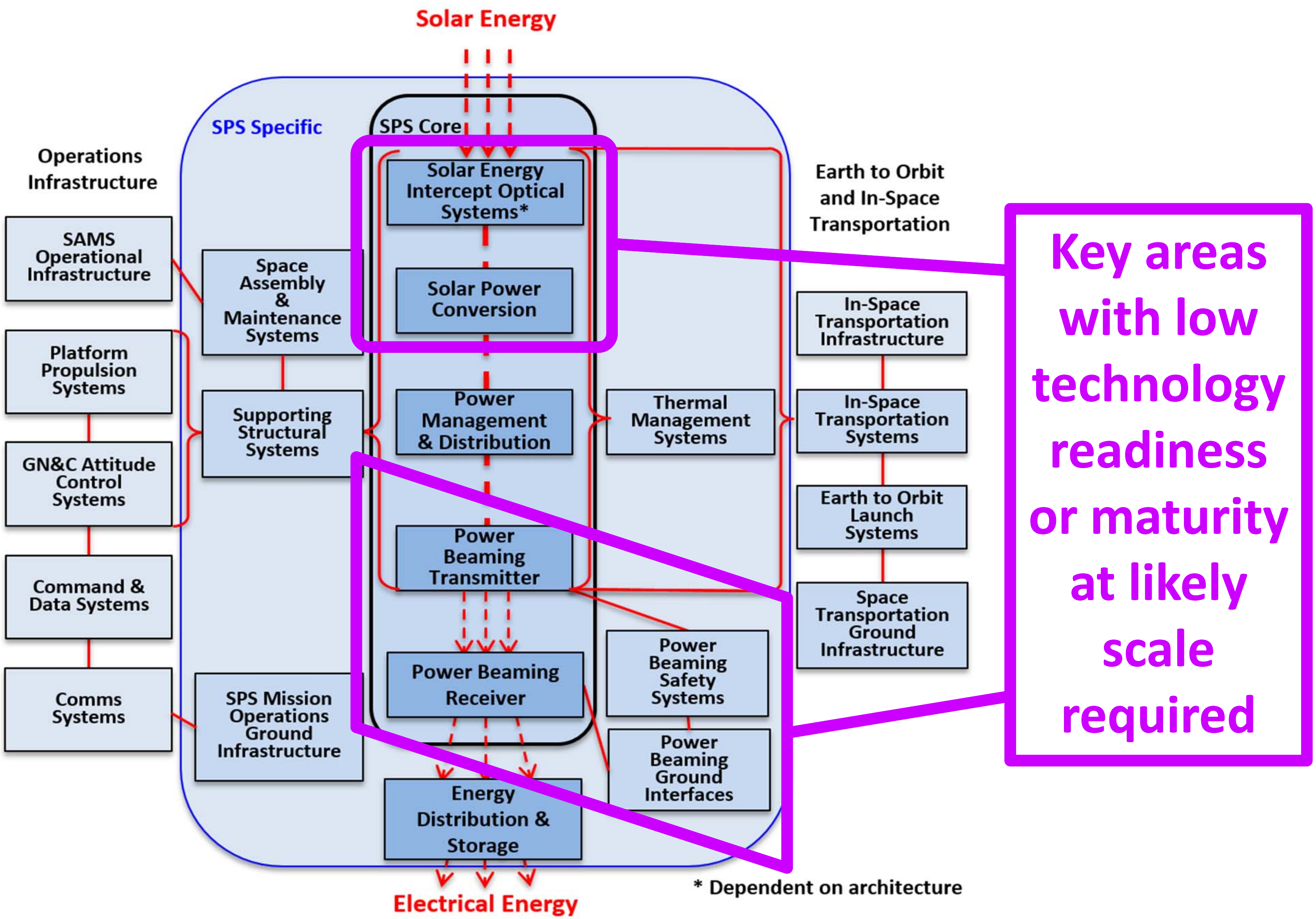
Abbreviations:

SPS = solar power satellite

SAMS = space assembly & maintenance systems

GN&C = guidance, navigation and control

Adapted from *The Case for Space Solar Power* by John Mankins



Scope of the 2019 study "Opportunities and Challenges for Space Solar for Remote Installations"

Goal

- Assess the feasibility of remote installation energy resupply via space solar

Objectives

- Identify key opportunities and challenges
- Create analytically underpinned, actionable recommendations

Methodology

- Combine lines of inquiry previously considered mostly in isolation to formulate:

(1) an assessment of space solar specifically for remote installations,
(2) systems suitable for power levels significantly lower than the utility grid,
(3) detailed identification of technology gaps,
(4) an evaluation of space solar in the context of current and future alternatives, and
(5) a consideration of future paradigms with increasing electrification and automation

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Study Summary Findings

The study team determined that there remain significant unresolved challenges inherent in the development of a practical, deployable space solar capability

To resolve the challenges, measured investment in six key areas should be undertaken by stakeholders:

1. Space Solar Collection
2. Power Beaming Transmission
3. Power Beaming Reception
4. Receiver Power Distribution
5. Architecture Analytics
6. Supporting Technologies

Opportunities

(1) Realization of technology dividends

Pursuing the tech needed for space solar has intrinsic value and broad applicability

(2) Pathfinding of future energy architectures

Space solar and power beaming unlock novel possibilities for autonomous and distributed systems

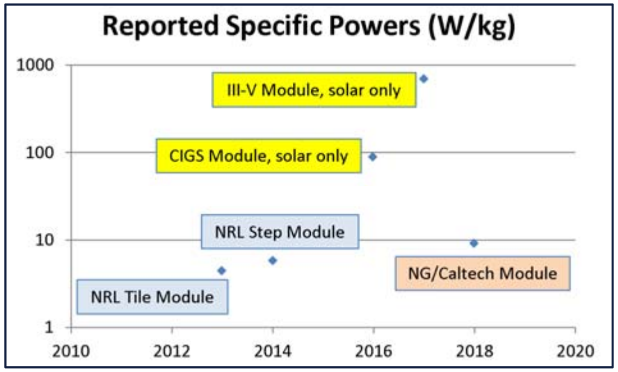
(3) Establishment of national leadership

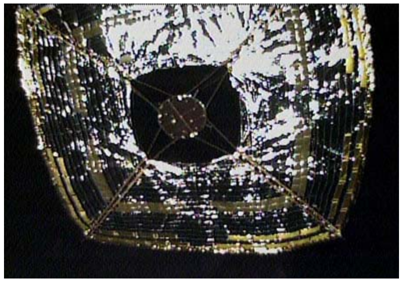
Benefits are realizable for defense, diplomacy, development, and domestic economic growth

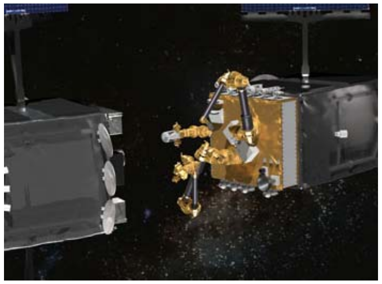
Challenges (chart 1 of 4)

Technical

- *Mass specific power needs to increase*
  - Current hardware has demoed transmitted power <10 W/kg
- *Minimal prototyping – technology immaturity*
  - Most power beaming demos were long ago
  - Need: Safe, high power, long distance power beaming; cheap space-rated photovoltaics
- *Unprecedented area-to-mass ratios*
  - Large collection areas needed in space
  - Solar wind effects, material rigidity, strength limits
- *Lifetime and serviceability uncertainty*
  - Capabilities for servicing of spacecraft not yet at required level of sophistication







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Technology Readiness Levels

System or Subsystem		TRL	Notes
Space Solar Power System		**5*/4***	**RF / Laser - *Note component TRLs below are not demonstrated at scale or cost point likely required for space solar***
Operations		**5**	**Lessons from decades of crewed spaceflight and satellite operations**
	Space Assembly and Maintenance Systems	6	Capability demoed in LEO (ISS), GEO DARPA Program in development (RSGS)
	Platform Propulsion Systems	9	Chemical and electrical systems on orbit, but not at required scale
	GNC Attitude Control Systems	6	Not yet demonstrated at space solar scale
	Supporting Structural Systems	5	Extremely high area to thickness ratios drive likely required
	Command / Data Systems	9	Decades of heritage
	Communications Systems	9	Extensive heritage on satellites
	Mission Operations Ground Infrastructure	7	Scale needed to support space solar ops still conceptual
Solar Energy Interception and Conversion		**6**	**Conventional spacecraft heritage**
	Solar Power Generation	9/6/4	PV / heat engine / solar-pumped laser; but none at required scale or cost
	Power Management & Distribution	6	Must manage losses and waste heat, highly architecture dependent
Thermal Management Systems		**6**	**Lower masses likely needed for space solar, not demonstrated at scale**
Power Beaming Transmitters		**6/5**	**Subscale RF demos in lab, outside, space / laser demos in lab and outside**
Power Beaming Receivers		**6/5**	**Rectennas below 100 GHz / laser receiver PV**
Power Beaming Safety Systems		**5/4**	**Preliminary demos performed for RF / laser**
	Retrodirection	5	Several Japanese-led demos
	Other Safety Systems	5/4	Power density and power beaming modality will affect safety systems
Ground Interfaces, Including Storage		**6**	**Not yet prototyped for space solar, but likely similar to ground solar**
In-Space Transportation Systems		**6**	**Dependent on implementation, possible GEO stationkeeping precursors**
Earth-to-Orbit (ETO) Launch Systems		**8**	**Reusable Falcon 9 or Heavy, reflight frequency likely needed not demoed yet**

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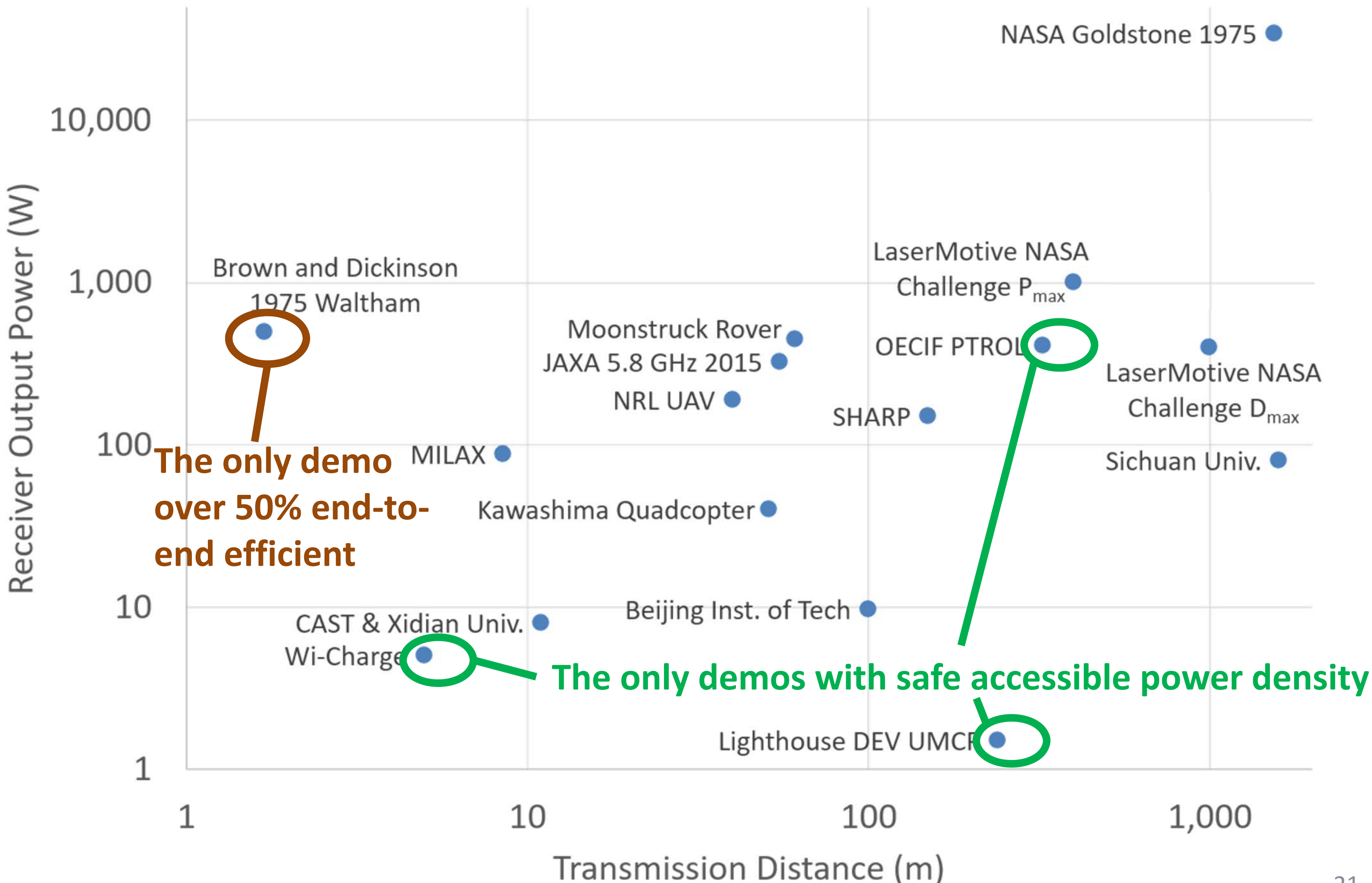
Receiver Power Output vs. Transmission Distance



Receiver Power Output vs. Transmission Distance

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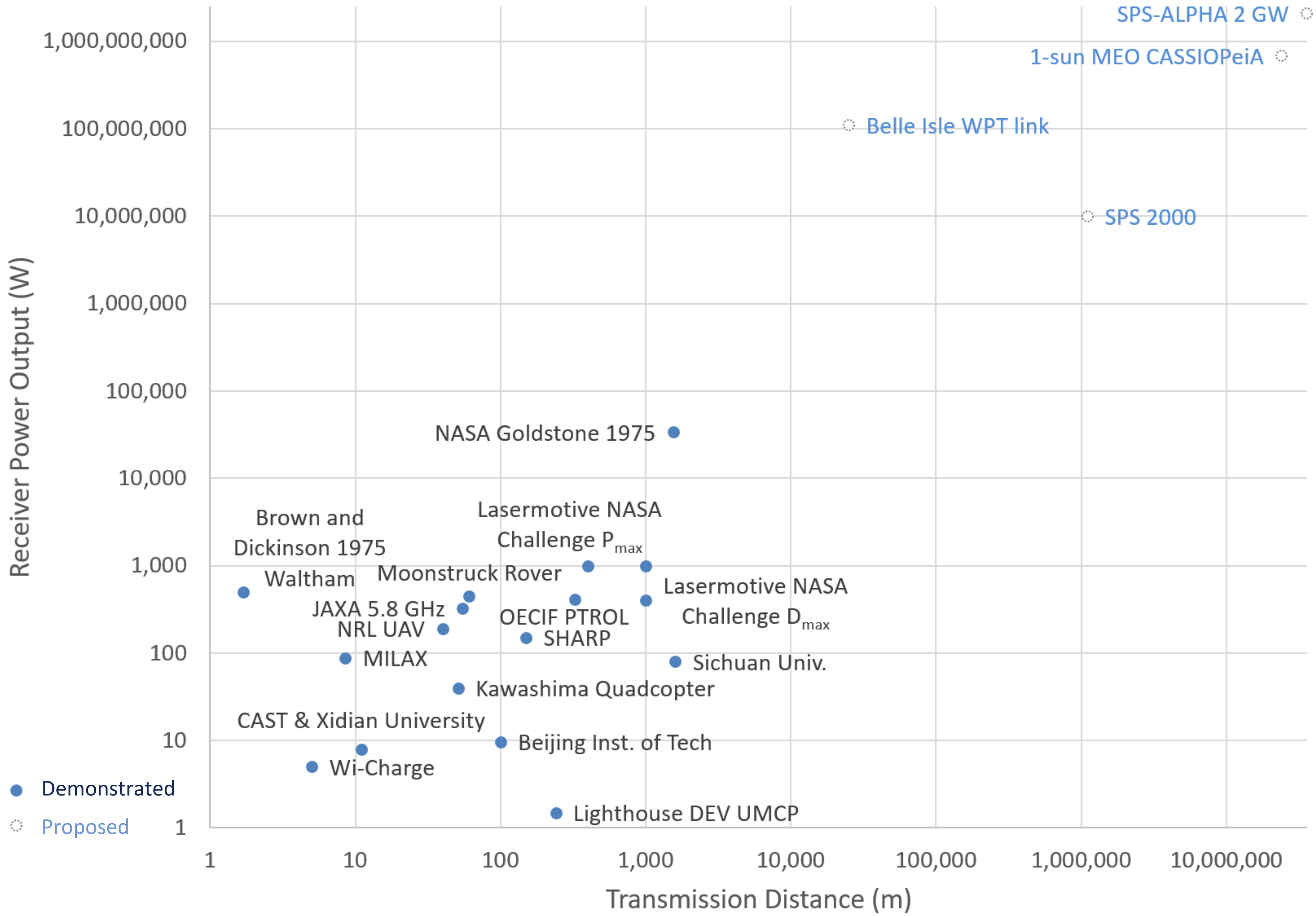

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Challenges (chart 2 of 4)

Economic

- *High capital and development costs*
  - Investment to operational capability >$Bs
  - Driven by launch, in-space transportation, hardware production, and R&D costs
- *Energy cost uncertainty*
  - Cost is challenging to forecast given uncertainties for both space solar and alternatives.

Legal/Political

- *Spectrum is not allocated for RF power beaming*
  - Electromagnetic interference risks
- *Safety and perceptions of safety*
  - Even if system is safe, there may still be public perceptions of hazards

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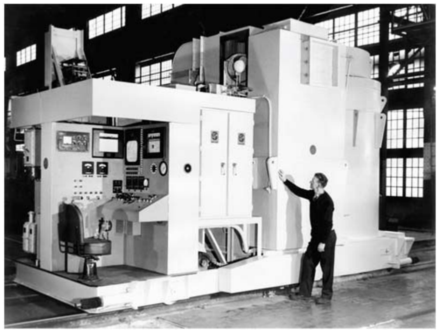
Challenges (chart 3 of 4)

Operational

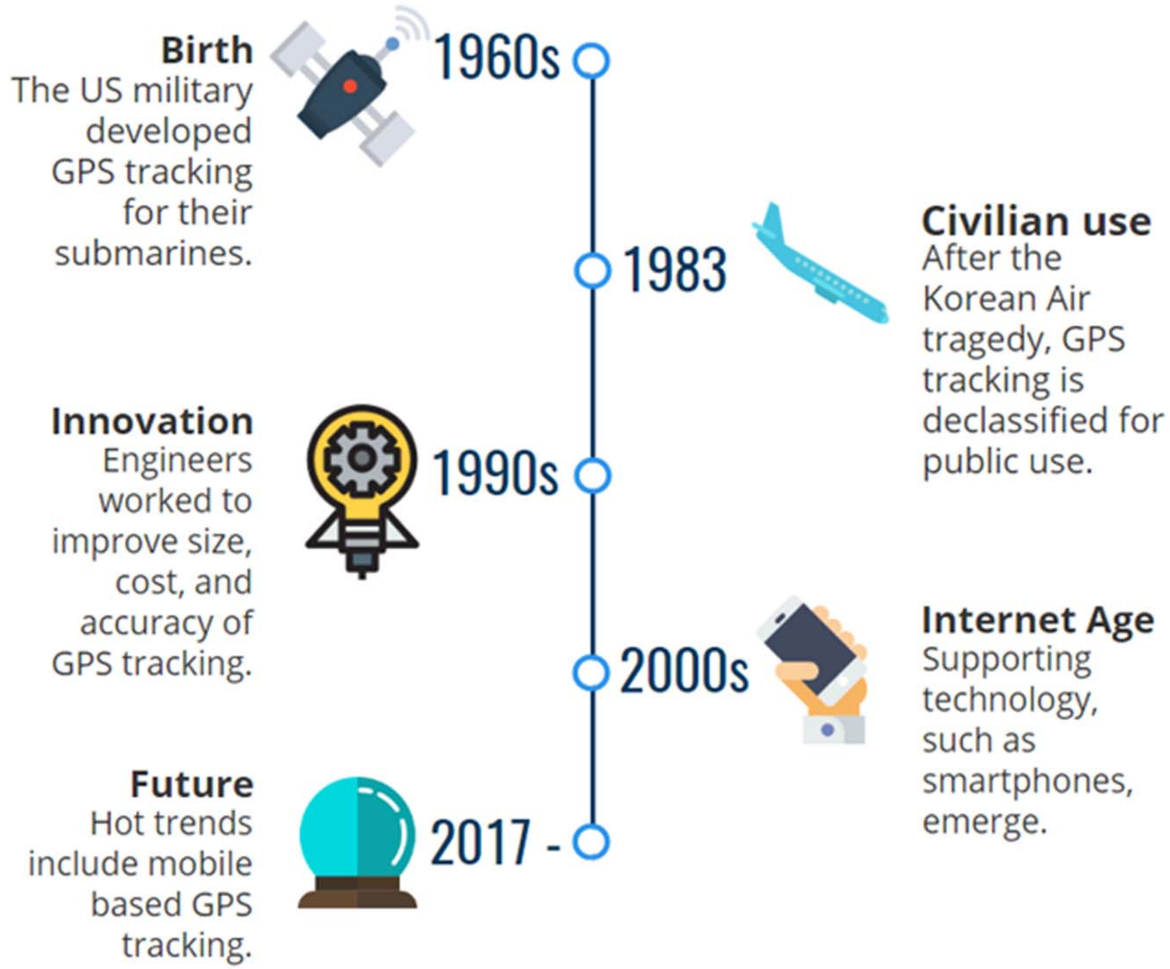
- *<u>Balancing power density safety and utility</u>*
  - Exceeding safety thresholds may raise weaponization concerns
- *Potential incompatibility with receiver site requirements*
  - Area may not be available for a large receiver
- *Mature alternatives*
  - Heritage solutions proven, have less cost uncertainty
- *The possible emergence of mobile nuclear*
  - Gaining traction, again
- *Susceptibility to disruption*
  - By hostile actors, solar activity, radiation, etc.



Challenges (chart 4 of 4)

Schedule

- *Long development timeline*
  - Might be like GPS, or not



GPS timeline image from: https://www.gofleet.com/wp-content/uploads/2017/05/gps-tracking-timeline_.png
"The Thens & Nows of GPS Tracking" by Jimmy Song, Jun 5, 2017

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Study Summary Recommendations

(1)Mature functional technologies:

a) Power beaming (transmission, reception, integration)

b) Space photovoltaics (lower cost, increase volume)

c) Architecture analytics

d) Integrating technologies

(2) Track metric progress every two years

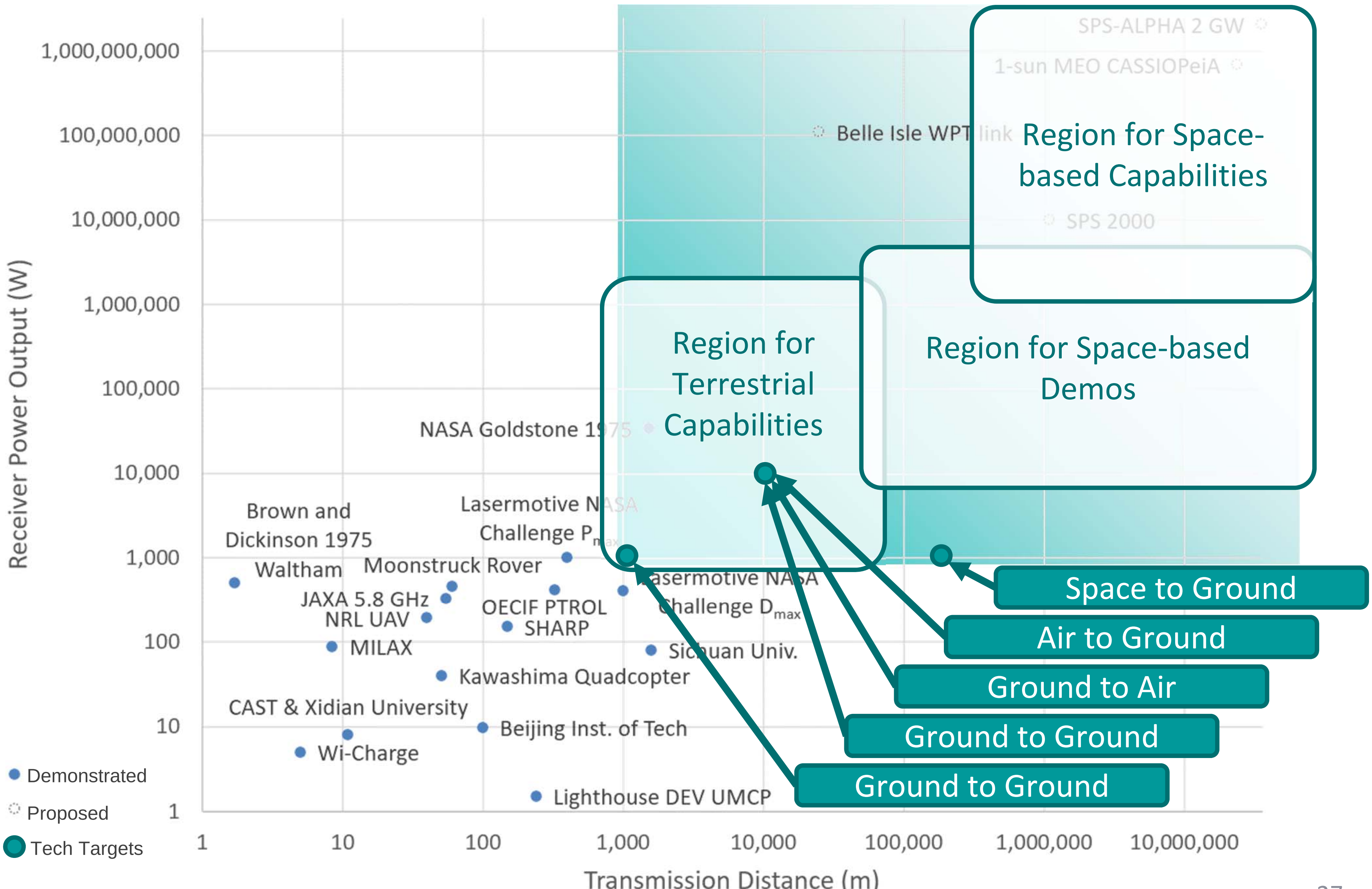
a) Launch cost ($/kg)

b) Space segment cost ($/kg)

c) Specific power (W/kg)

(3) Collaborate to share costs/benefits, address regulatory hurdles

Roadmap for Power Beaming Toward Near-term Applications and Space Solar



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Closing Thoughts

- History is built on contingencies
- Energy technology is of profound importance for humankind
- As new domains of human activity emerge in space and elsewhere, the energy and technologies needed to secure them must be developed as well
- The prospects for power beaming and space solar hold both compelling opportunities and formidable challenges, each of which will be illuminated first by those that move decisively and proactively

Chinese Perspective

"Whoever obtains the technology first could occupy the future energy market. So it's of great strategic significance." – Wang Xiji, Chinese space technology pioneer (Chief Designer of China's sounding rockets, first space launch vehicle, and first recoverable satellites), regarding space solar

Clean Energy Development and Utilization
高端清洁能源开发与利用——
Space Solar Power and Its Technologies
空间太阳能以及相关空间技术

Dr. Li Ming
李明 博士
The Vice President of CAST
中国空间技术研究院 副院长

- Three Conclusions from SPS research

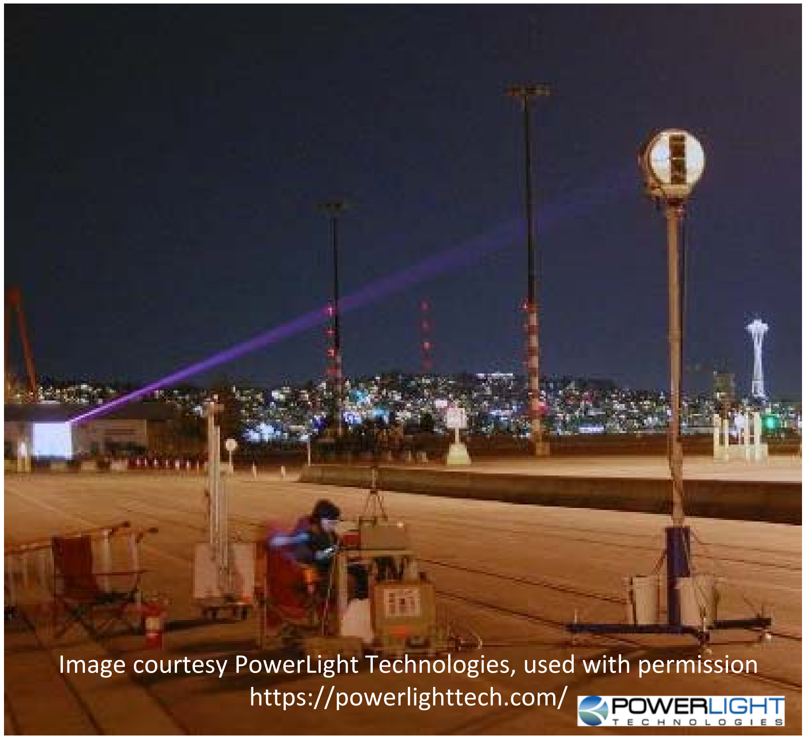
空间太阳能电站的三个重要结论

Space power is one of the important potential renewable energy in the future both for China and world.
空间太阳能对于中国和世界都尤为重要。

SPS is an incredible macro-engineering in space. There are still many technology challenges need to overcome
空间太阳能电站是一个庞大的工程仍然还有许多挑战需要克服。

SPS need more collaboration between different countries and organizations.
空间太阳能电站需要不同国家和不同组织的通力合作。

U.S. NAVAL RESEARCH LABORATORY



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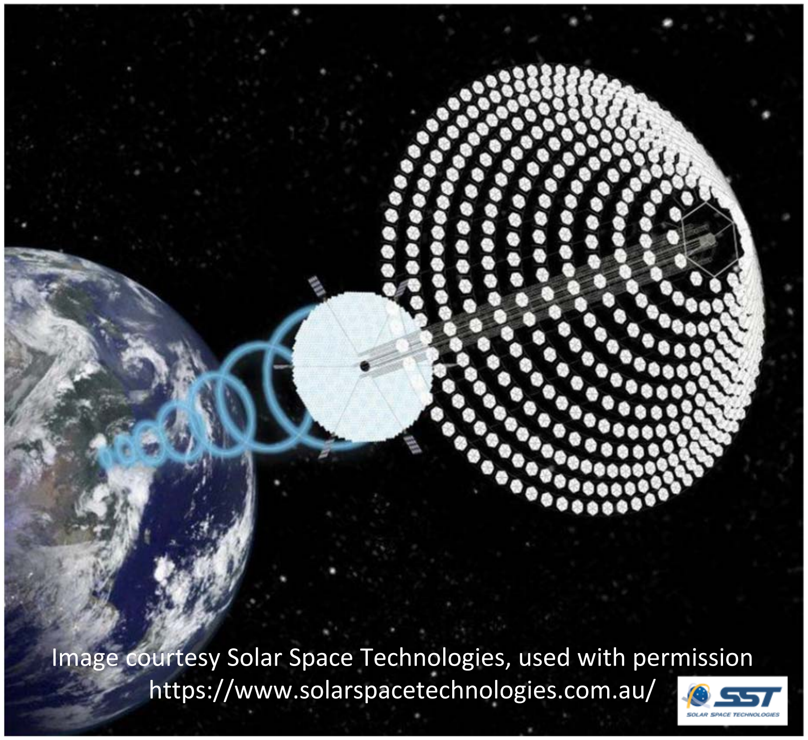

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Thank you for your attention

Paul Jaffe, PhD
202-767-6616
Paul.Jaffe@nrl.navy.mil