Raytheon

Wireless Power Beaming – The Future is Now

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RTN - Space and Airborne Systems

Wireless Power Beaming

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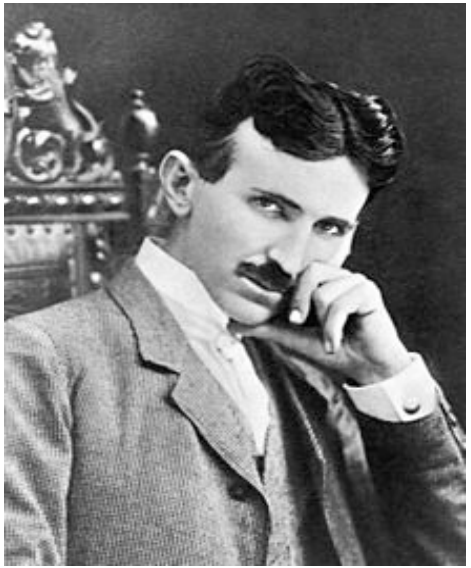
- Tesla's (1900) and Brown's (1965) pioneering work
- Historical Wireless Power Beaming efforts
- Power Beaming Components and Atmospherics
- Long-term Applications:
  - Space Solar Power, Space-to-Space, Ground- & Interstellar Propulsion
- Nearer-Term Applications:
  - Quad Copters, UAV's, LTA platforms
- Conclusions

Nikola Tesla, 1856-1943



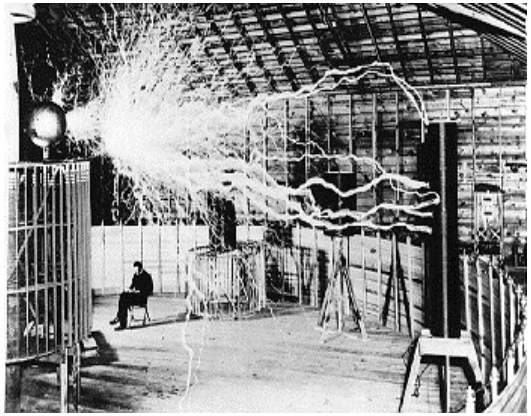
Born: 10 July 1856, Smiljan, Austrian Empire (modern-day Croatia)

Died: 7 January 1943(aged 86), New York City, New York, United States

Lifetime Pursuits:
Alternating current, high-voltage, high-frequency power, wireless power transmission

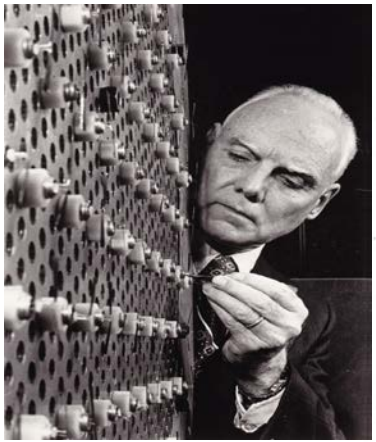
1899, Colorado Springs Lab:
Large oscillators; Transmitted at 150 kHz with potentials >100,000 kV

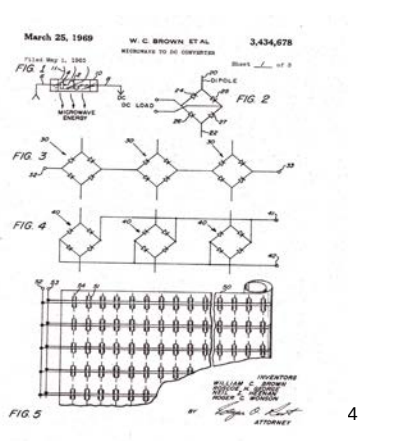
1901-03, Wardenclyffe Tower, NY:
World's first wireless power and communication station…lost funding



Bill Brown, Raytheon – RF Rectenna

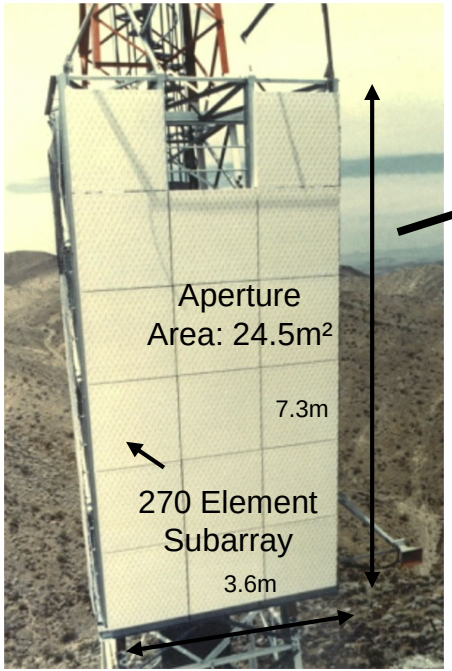
- 1963: First RF power capture 100W output power, 15% DC-to-DC efficiency; 2.45 GHz; at 5.5m distance
- 1965/1969: Invention of ~ 55% Rectifying Antenna (Rectenna) with George, Heenan, Wonson

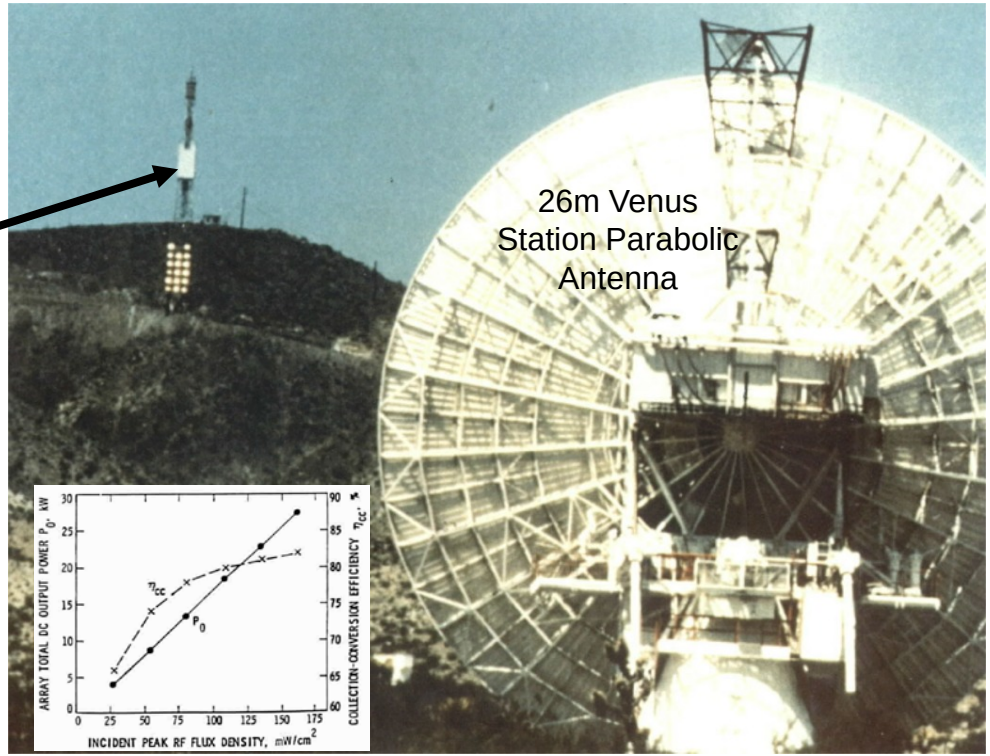




JPL - Raytheon Goldstone Experiment

- 1975: 34 kW collected from rectenna located 1 mile (1.54 km) from 320 kW transmitter

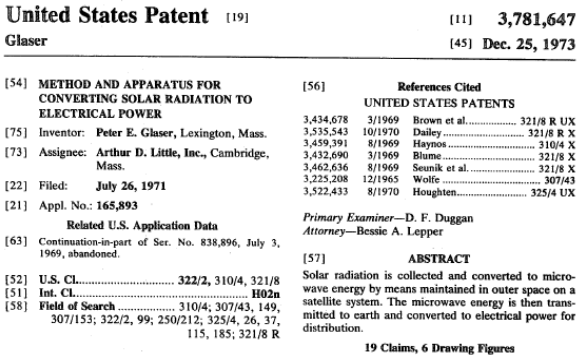




"Reception-conversion subsystem (RXCV) for microwave power transmission system, final report," Raytheon Company, Sudbury, MA, Tech. Report No. ER75-4386, JPL Contract No. 953968, NASA Contract No. NAS 7-100, Sept. 1975

Peter Glazer - Space Solar Power Satellite

- Born in Czechosolvakia 1923, died in Cambridge, Ma 2014
- VP, Advanced Technology, Arthur D. Little, Cambridge, Ma
- 1968/1973: Inspired by Brown's power beaming technology begins work on the Solar Power Satellite



United States Patent [19]
Glaser

[11] 3,781,647
[45] Dec. 25, 1973

[54] METHOD AND APPARATUS FOR CONVERTING SOLAR RADIATION TO ELECTRICAL POWER

[75] Inventor: Peter E. Glaser, Lexington, Mass.

[73] Assignee: Arthur D. Little, Inc., Cambridge, Mass.

[22] Filed: July 26, 1971

[21] Appl. No.: 165,893

Related U.S. Application Data

[63] Continuation-in-part of Ser. No. 838,896, July 3, 1969, abandoned.

[52] U.S. Cl. 322/2, 310/4, 321/8
[51] Int. Cl. H02n
[58] Field of Search ..... 310/4; 307/43, 149, 307/153; 322/2, 99; 250/212; 325/4, 26, 37, 115, 185; 321/8 R

[56] References Cited
UNITED STATES PATENTS

3,434,678	3/1969	Brown et al.	321/8 R UX
3,535,543	10/1970	Dailey	321/8 R X
3,459,391	8/1969	Haynos	310/4 X
3,432,690	3/1969	Blume	321/8 X
3,462,636	8/1969	Seunik et al.	321/8 X
3,225,208	12/1965	Wolfe	307/43
3,522,433	8/1970	Houghten	325/4 UX

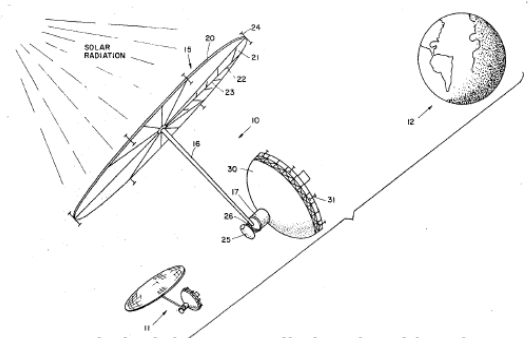
Primary Examiner—D. F. Duggan
Attorney—Bessie A. Lepper

[57] ABSTRACT

Solar radiation is collected and converted to microwave energy by means maintained in outer space on a satellite system. The microwave energy is then transmitted to earth and converted to electrical power for distribution.

19 Claims, 6 Drawing Figures

Solar Power Satellite Patent



Non-Export Controlled – See Slide 1

Power Beaming Applications

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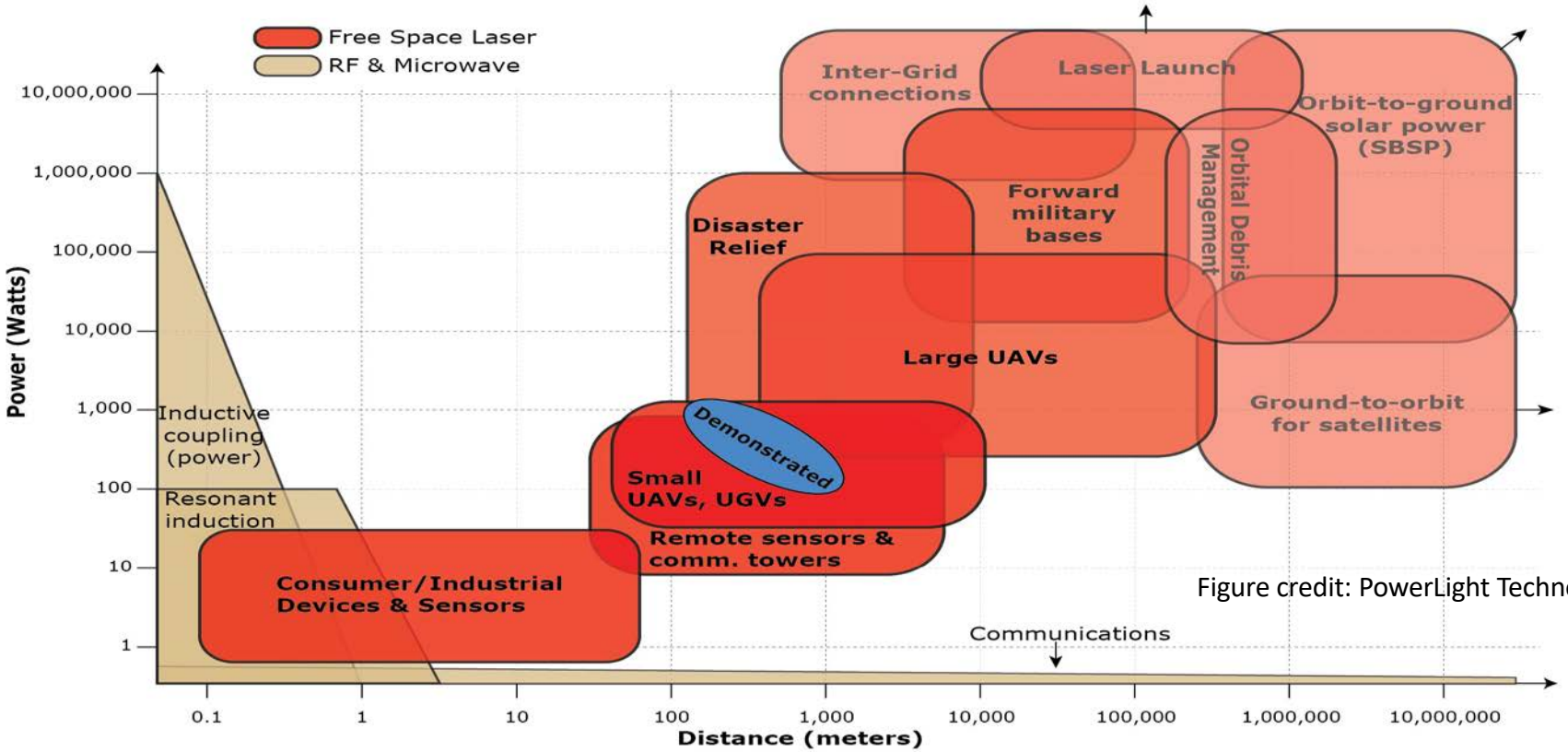

Figure credit: PowerLight Technologies

ATTENUATION OF EM WAVES BY THE ATMOSPHERE

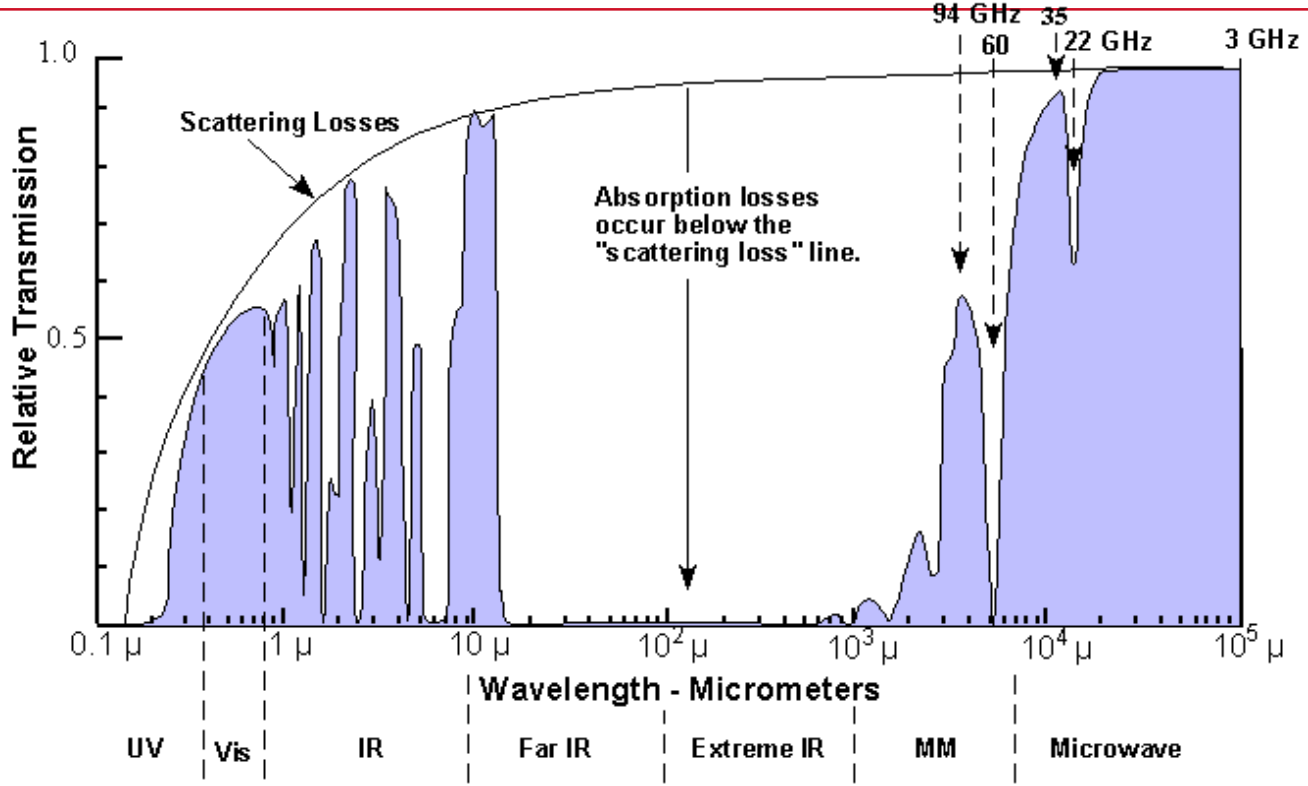

Figure from https://upload.wikimedia.org/wikipedia/commons/7/78/Atmosph%C3%A4rische_Absorption.png

Solid-State RF Amplifiers

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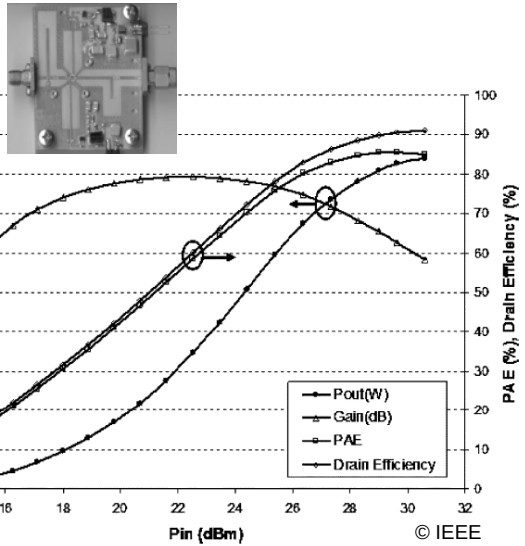
- 85% power added efficiency (PAE) at 2 GHz for a GaN amplifier [1]
  - 16.5 W, 12 dB Gain, 42.5V Drain Bias



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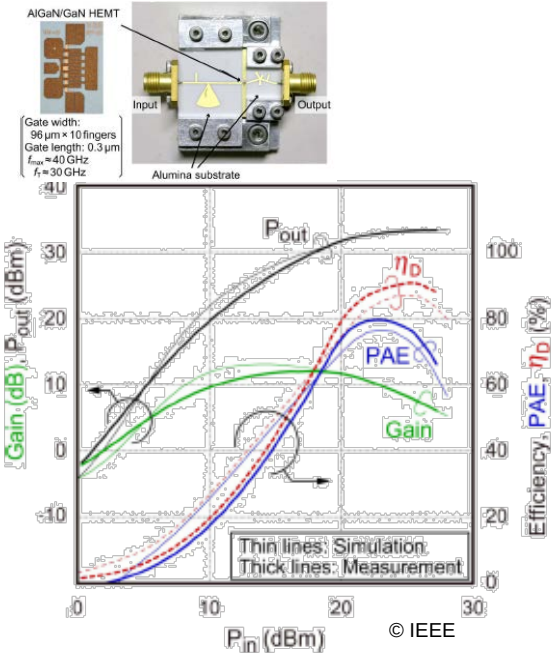
[1] D. Schmelzer and S.I. Long, "A GaN HEMT class F amplifier at 2 GHz with > 80% PAE," IEEE Journal of Solid-State Circuits," vol. 42, no. 10, pp. 2130-2136, Oct. 2007.

[2] M. Kamiyama, R. Ishikawa, and K. Honjo, "5.65 GHz high-efficiency GaN HEMT power amplifier with harmonics treatment up to fourth order," IEEE Microwave and Wireless Components Letters, vol. 22, no. 6, pp. 315-317, June 2012.

- 79% PAE at 5.65 GHz for a GaN HEMT amplifier [2]
  - 2.1 W, 11 dB Gain, 20.5V Drain Bias



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High power and high efficiency GaN amplifiers have been demonstrated

Solid State Optical Components

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Advanced Laser Pump Modules ~65%

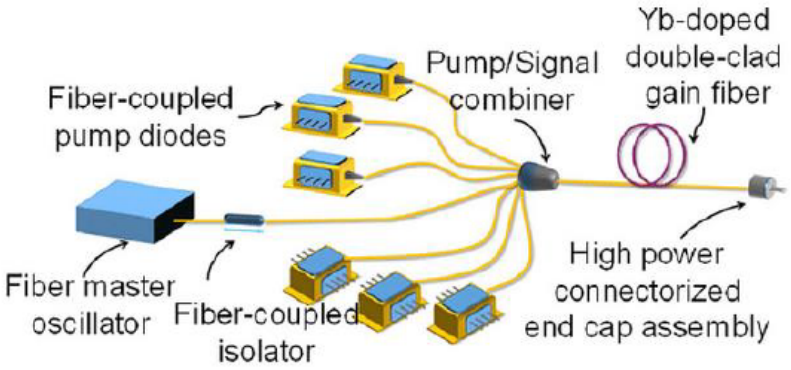
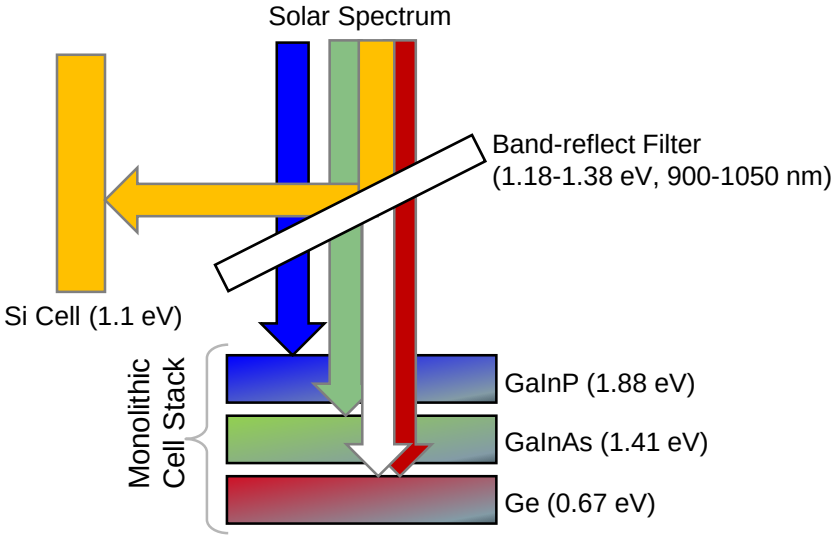


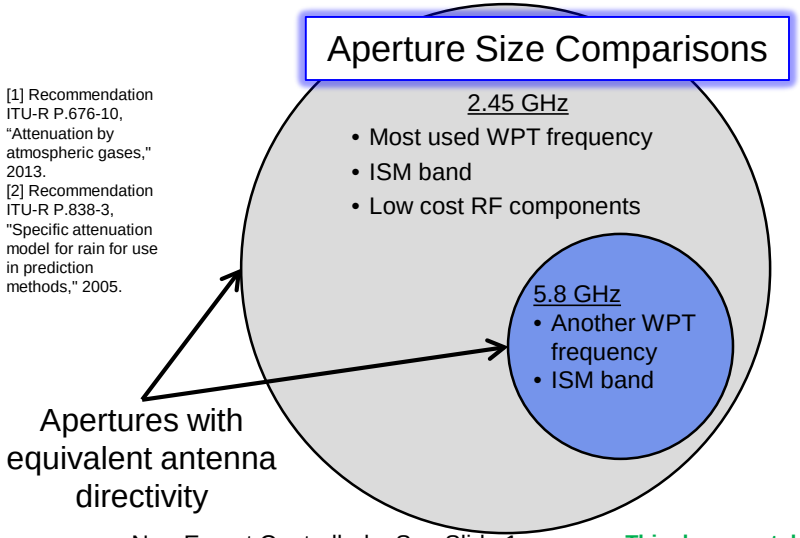
Figure 4.3 Graphic schematic of a pumped Yb fiber laser [68].



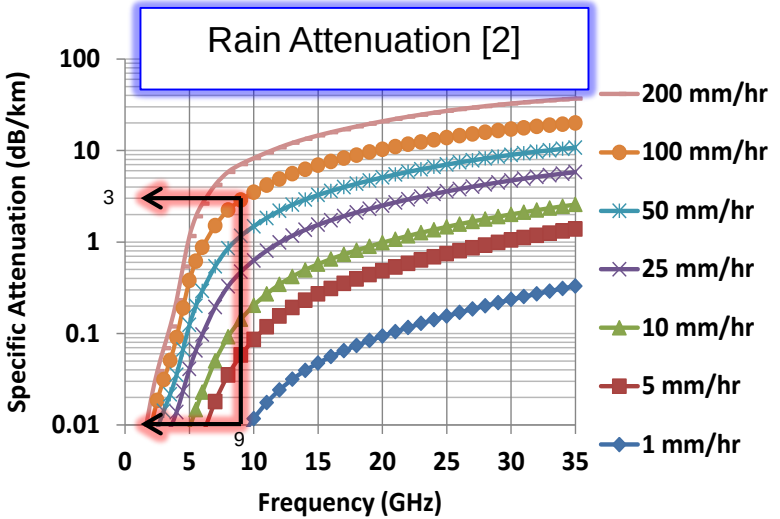
Multi-junction photocells ~ 40% for Sunlight
Tuned PV ~ 65% (lab exp)

Atmospheric & Physical Realities

Higher RF frequencies allow smaller apertures but provide lower RF efficiencies



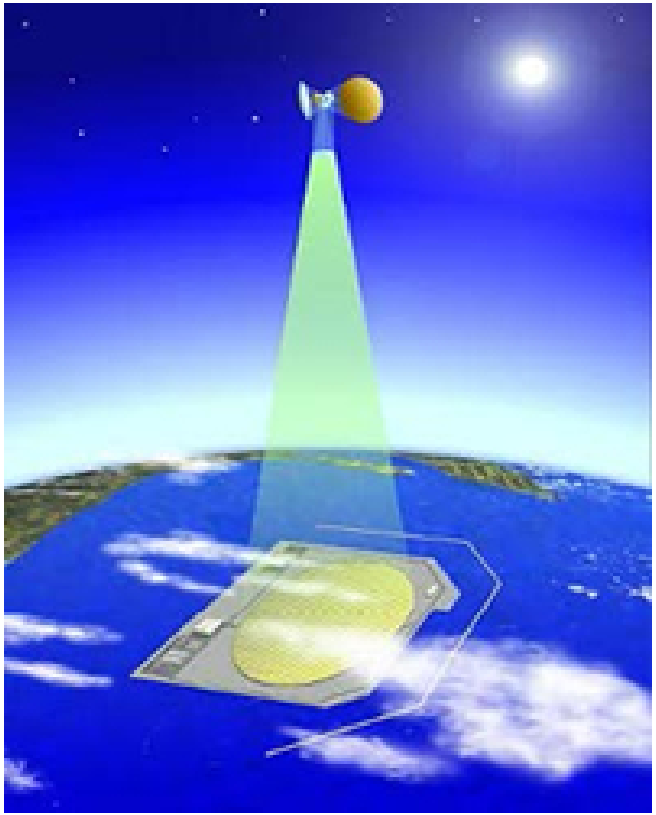
[1] Recommendation ITU-R P.676-10, "Attenuation by atmospheric gases," 2013.
[2] Recommendation ITU-R P.838-3, "Specific attenuation model for rain for use in prediction methods," 2005.

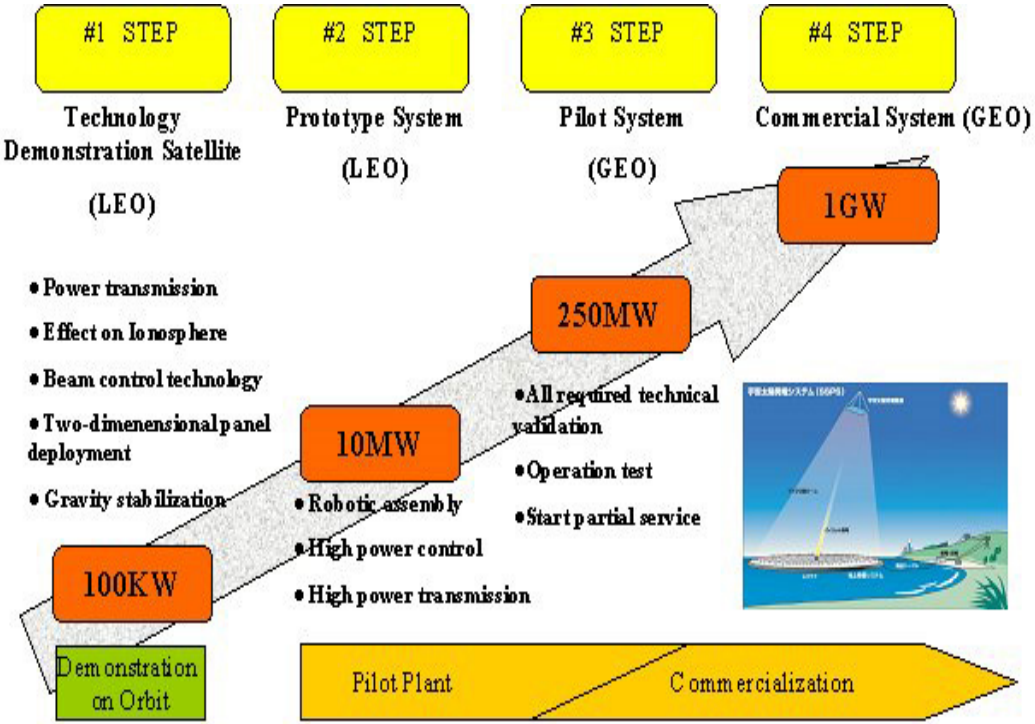


At low RF frequencies (<9GHz) rain/fog does not greatly attenuate power beam

Non-Export Controlled – See Slide 1

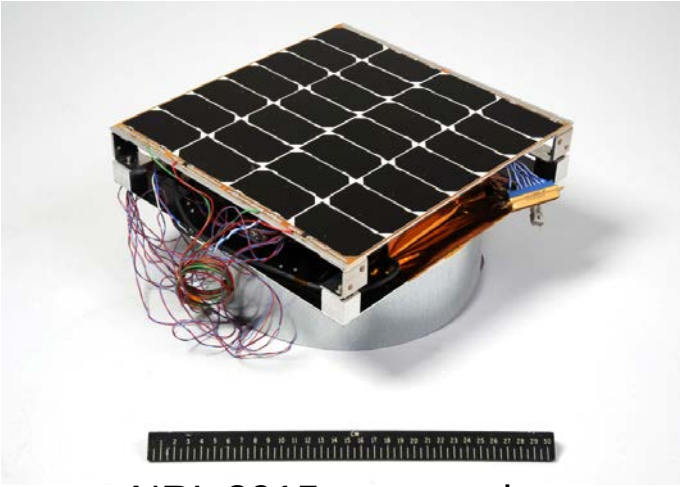
JAXA – Space Solar Power System 2000 -





Mankins – NASA SPS-ALPHA – 2010-

- John Mankins – Artemis Innovations (former NASA)
- 5.1-5.8GHZ, 10MW Solar Power Satellite with Arbitrarily Large Phased Array (SPS-ALPHA) in LEO and GEO versions



NRL 2015 space solar conversion module prototype

U.S. Air Force Research Laboratory Developing Space Solar Power Beaming -$100M to NGC, 10/24/2019

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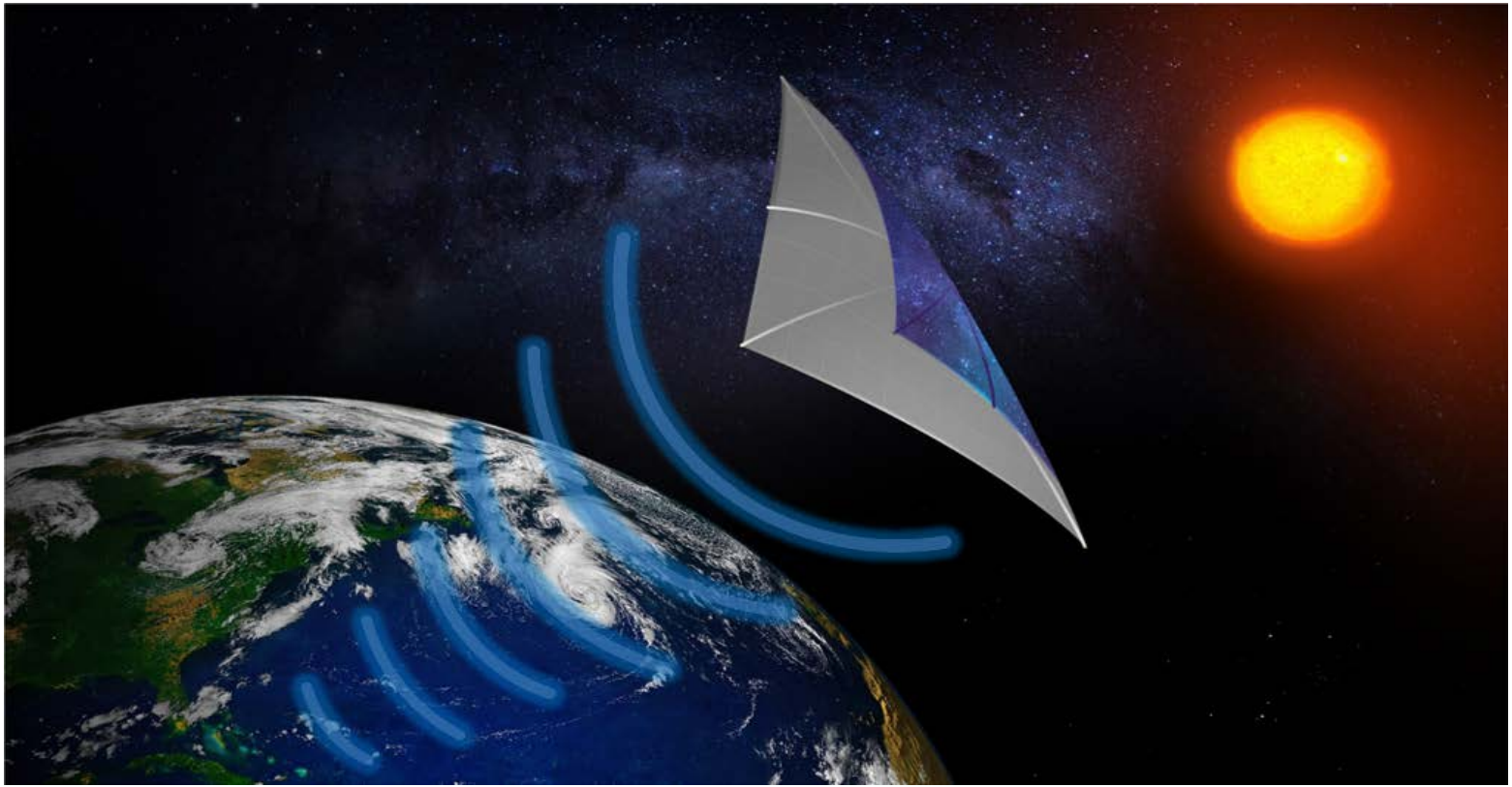
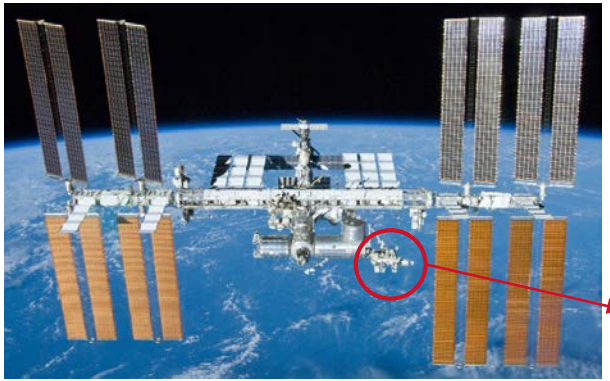


Space-to-Space Power Transfer – Low Power

- Deliver power to orbital sensors and transmitters onboard Small Sat's
- Provides continuous power through Dark and light, reducing overall weight
- Wireless power delivery of <100W is generally the need for small spacecraft
- Power radiated sources can be onboard of larger installations
- Space station currently has 90 kW of prime power
- Size and Weight of the receiving antennas are most important (< 1kg/m^2)
- Lasers radiated power is a realistic option in space but RF power is currently Lower SWAP



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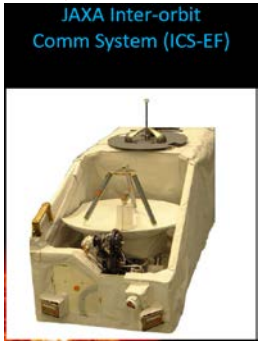
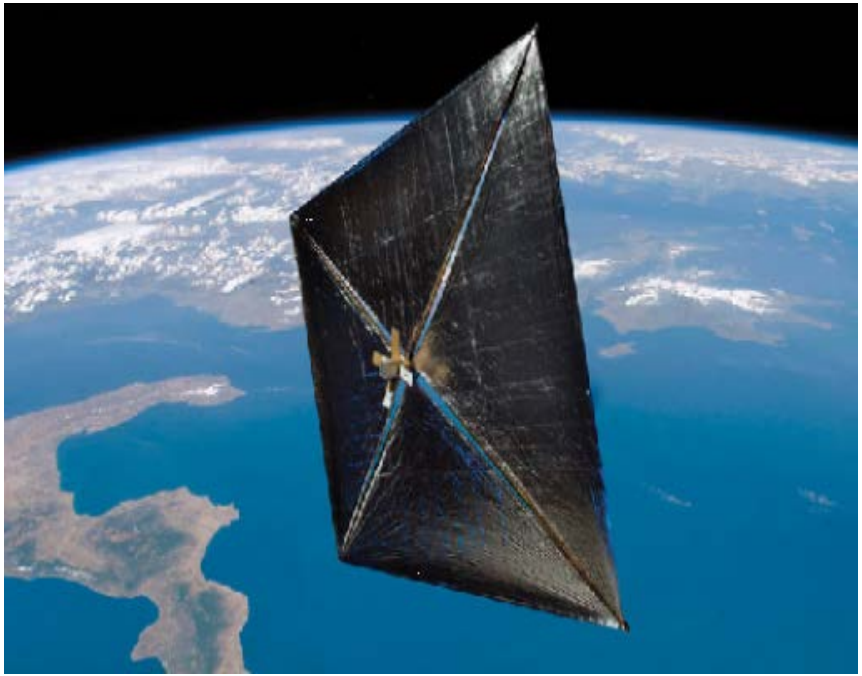
MicroSat remote wireless power feed

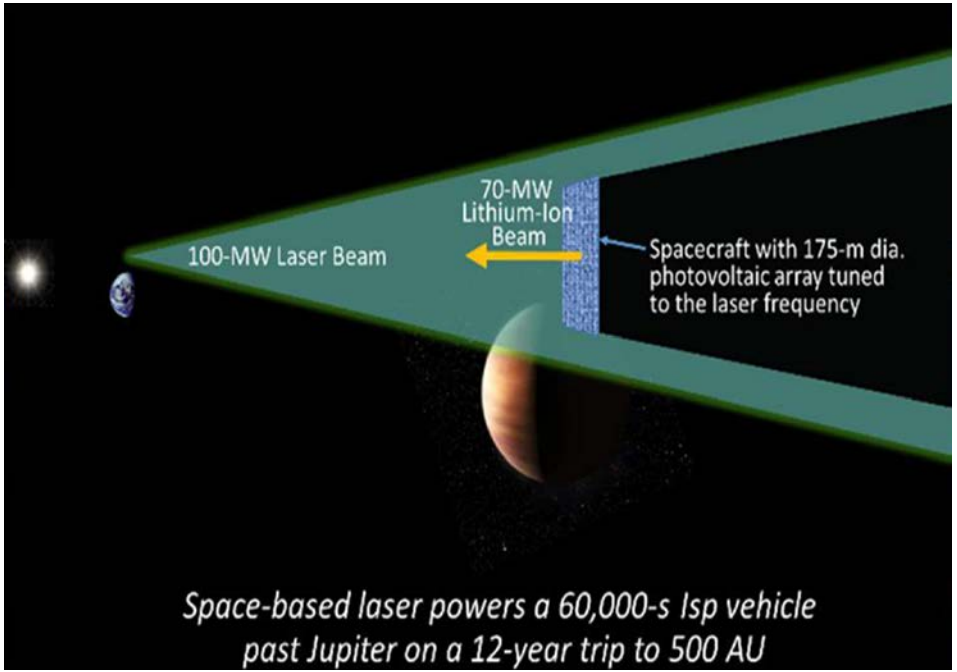
RF Power radiated to MicroSat



Courtesy of NASA

Space-to-Space Power Transfer – High Power





John Brophy, NASA Jet Propulsion Laboratory, 4/6/17

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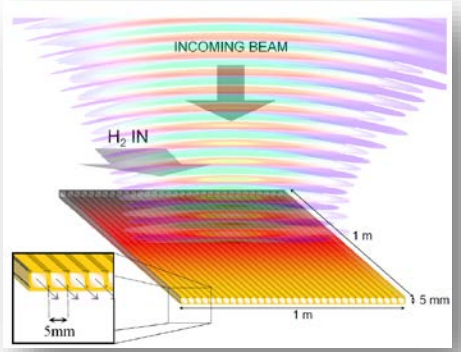
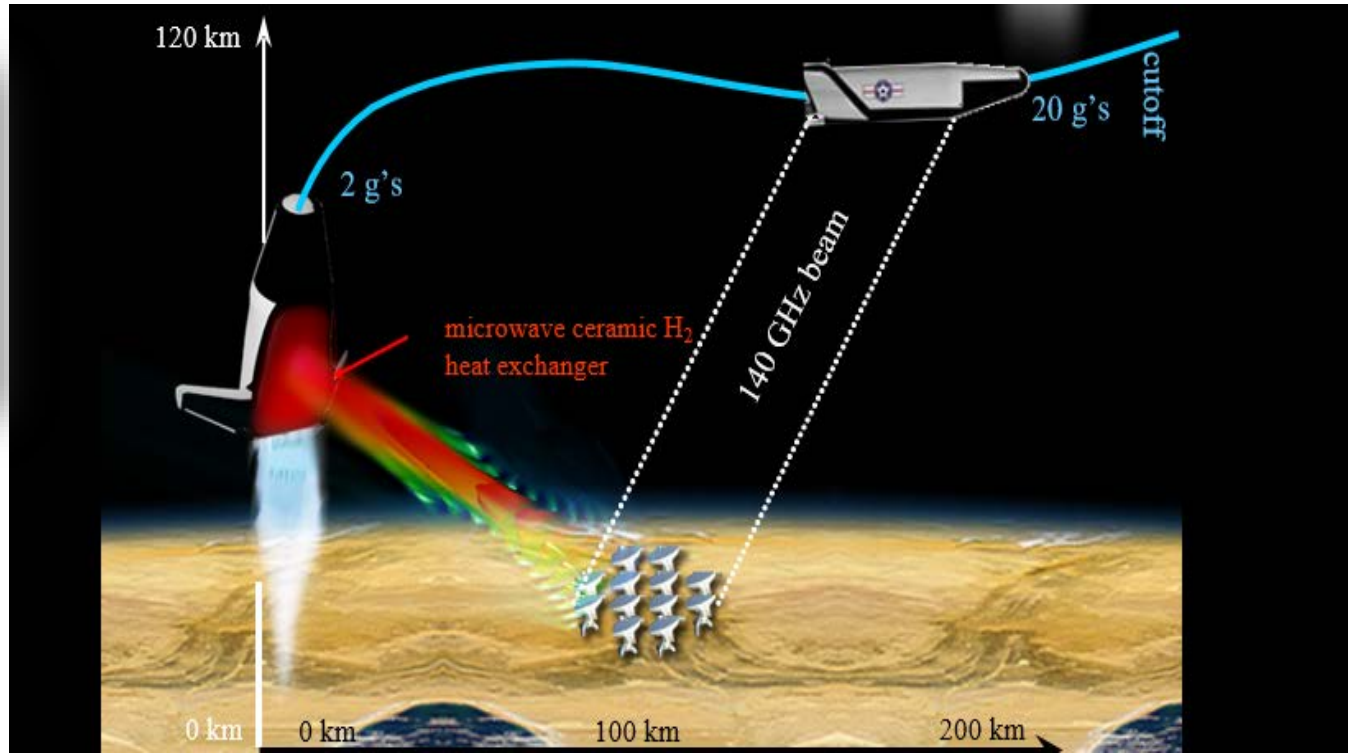
Laser “Sail”

Deep Space Interstellar Propulsion System

Directed Microwave Energy enables high Thrust-to-Weight Ratio circa 2012



- Hydrogen fuel with a thermal heat exchanger for high ISP
- Successful laboratory experiments
- Full scale implementation still awaits



Reference: http://parkinresearch.com/microwave-thermal-rockets/
Used with the prior permission of NASA, Caltech and Dr. K. L.G Parkin)

Recent Microwave Power Beaming Experiments

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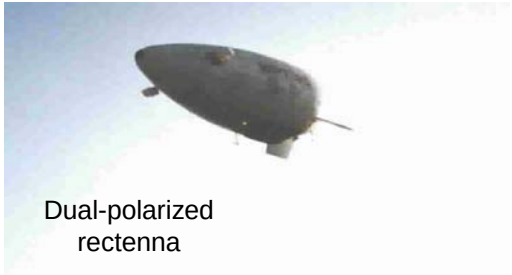
Canadian
SHARP 1987 (10 kW)

Japanese MILAX 1992
(1.25 kW)

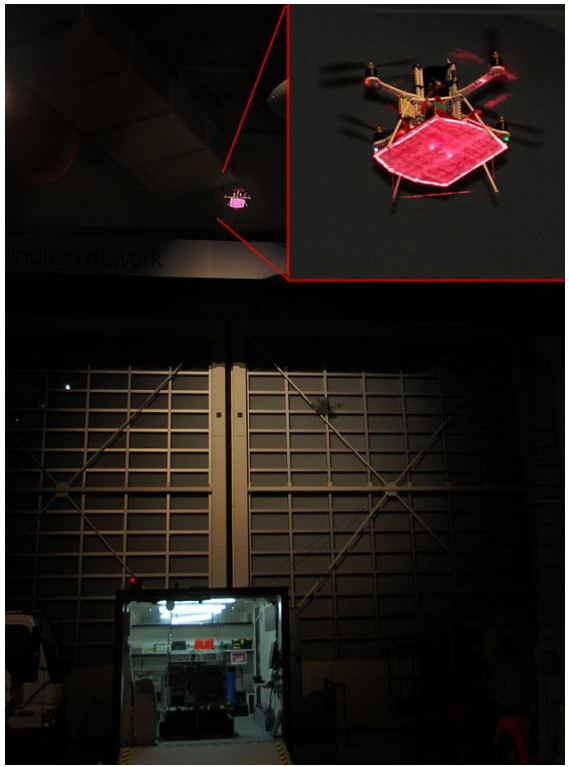
Japanese ETHER
1995 (10 kW)



Dual-polarized
rectenna

10 kW 3m diameter
dual-polarized
transmitter

Laser Power Beaming - PowerLight Technologies Quadcopter Demo



- With Ascending Technologies (later bought by Intel)
- Specific power ~ 0.8kW/kg
- 12.5 hour flight (with 5 minute battery), limited only by venue
  - Recharge battery during flight after off- beam flight times
- Automatic tracking, including auto-acquisition
  - Plus sending location to multicopter as pseudo-GPS
- Multiple records for power beaming duration and UAV endurance

This chart is presented with the permission of PowerLight Technologies

Laser Power Beaming – PowerLight Technologies Fixed Wing UAV Demo

- Receiver designed for 2x average flight power
- Ground proof-of-concept operated 48+ hours continually, verified functionality
- Outdoor flights: Day & night, strong winds
- Tracking accurate to ~20 microradians, 1cm @ 500 m
- Altitudes up to 2,000 feet (600 meters)
- Automatic beam shut-off if >5 cm off center, when entering Laser Clearinghouse-defined windows
- Robust receiver: undamaged even on landings causing airframe damage

This chart is presented with the permission of PowerLight Technologies

Forward Power Distribution Network

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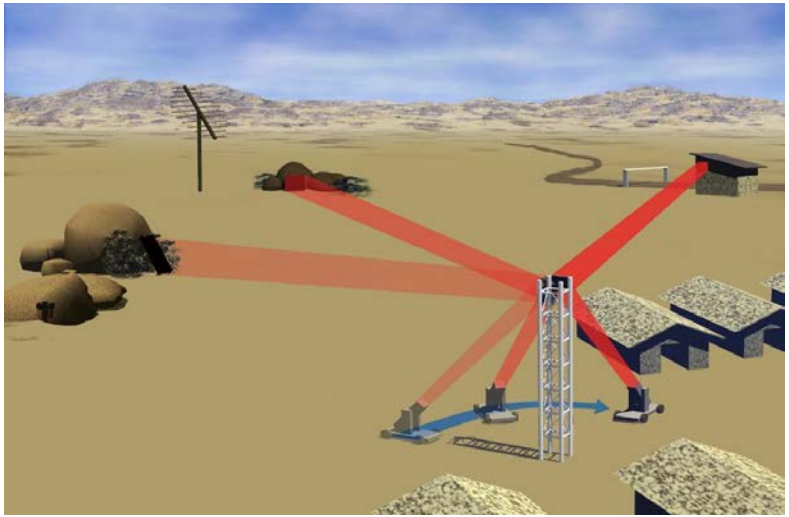

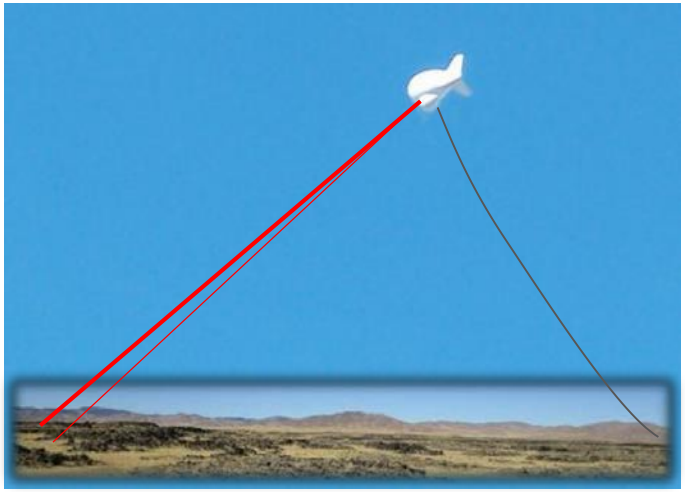

Increased:

- Power distribution flexibility
- Resilience

Specific applications:

- Remote site energy resupply
- Ship-to-shore energy provision
- Unattended sensors

Conclusions

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1. Power Beaming an emerging disruptive technology for long-term and nearer-term applications – The Future Is Now!
2. Multiple system architectures evolving to meet system design trade-offs
    - Wavelength and antenna aperture diameter
    - "Spot Size," beaming distance, environmental impact
    - Assuring safety and control of beam front
3. Ongoing development of RF and HEL & PV component technologies enabling accelerated development