Millimeter wave Wireless Power Transmission Technologies and Applications

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Raytheon Space and Airborne Systems

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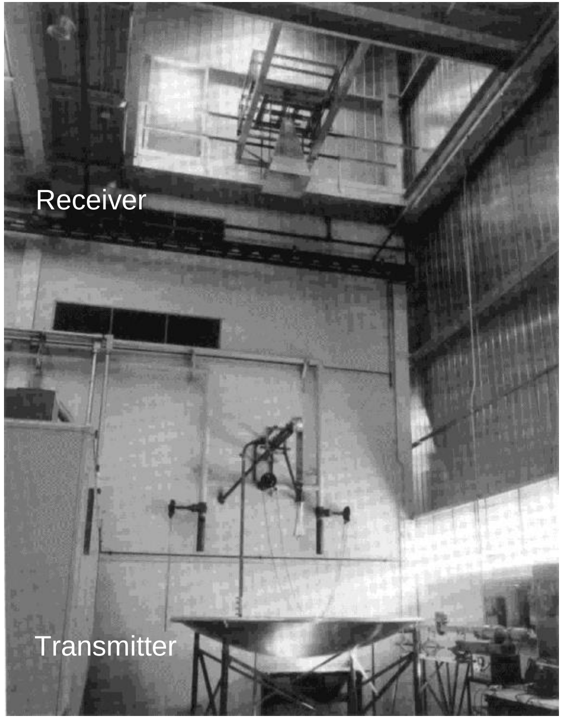
Presentation Overview

- The RF Wireless Power Beaming history and notable demonstrations to date
- Millimeter wave Power beaming analysis and key advantages
- Millimeter wave Transmitter Technology
- Millimeter wave Rectifier Technology

Raytheon's First Major Demo

Raytheon

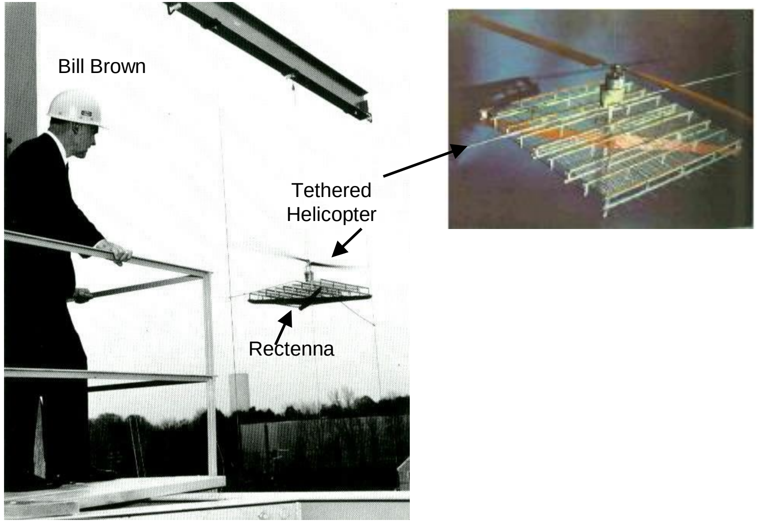
- 1963: First modern microwave power transmission system conducted in Raytheon's Spencer Lab in Burlington, MA
  - Horn antenna receiver using close-spaced thermionic rectifying diodes at 50% efficiency
  - 100W output power
  - 2.45 GHz power beaming at 5.5m distance
  - 15% overall DC-to-DC efficiency
  - Demo resulted in an Air Force contract for powering a flying communications platform



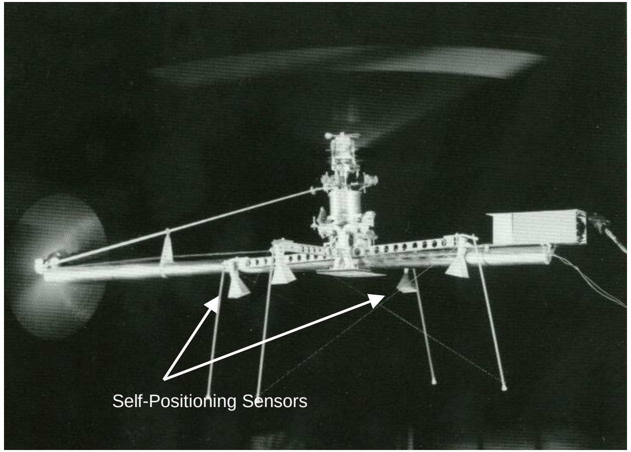
"W. C. Brown, "Electronic and mechanical improvement of the receiving terminal of a free-space microwave power transmission system," Raytheon Company, Wayland, MA, Tech. Report PT-4964, NASA Report No. CR-135194, Aug. 1977.

Raytheon's Helicopter Demos

- 1964: Tethered helicopter powered at 2.45 GHz with continuous flights up to 10 hours with first rectenna at distance of 18.3m
- 1968: Developed self-positioning sensors to automatically position over power beam



"W. C. Brown, "Electronic and mechanical improvement of the receiving terminal of a free-space microwave power transmission system," Raytheon Company, Wayland, MA, Tech. Report PT-4964, NASA Report No. CR-135194, Aug. 1977.

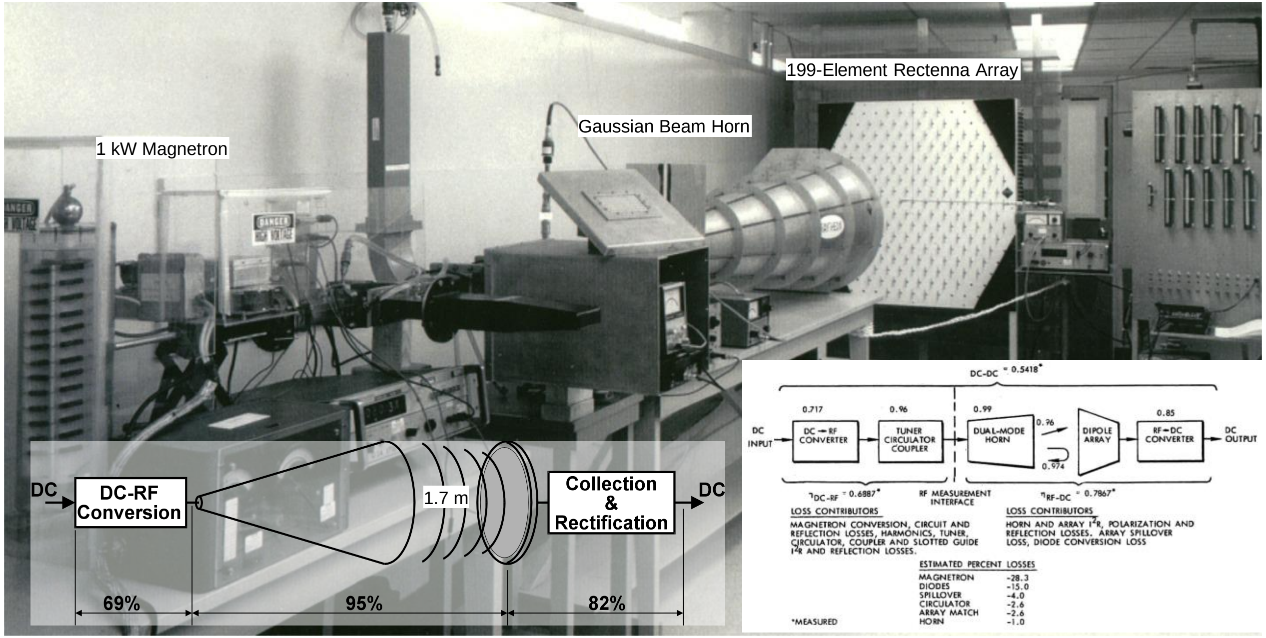


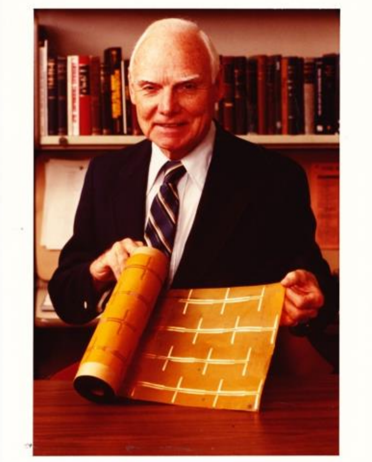
"W. C. Brown, "Experimental system for automatically positioning a microwave-supported platform," Raytheon Company, Burlington, MA, Tech. Report PT-1751, Air Force Contract AF30(602)-4310,June, 1968.

JPL - Raytheon DC-DC Efficiency Record

Raytheon

- 1975 measurement confirmed a 54% DC-DC system efficiency at 2.45 GHz
- 485 W DC rectenna output power





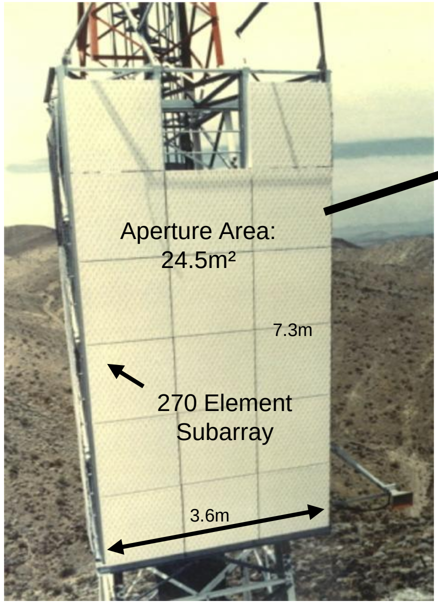
William Cyrus "Bill" Brown
1916-1999

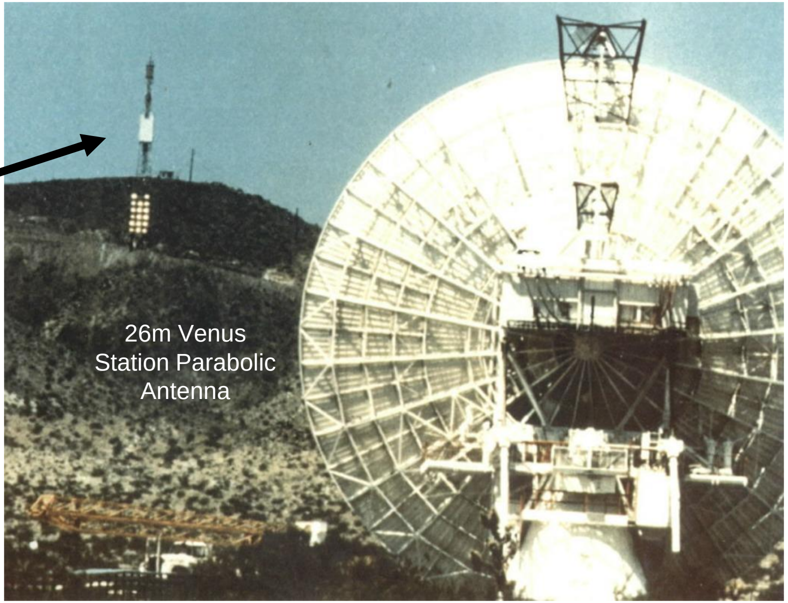
"W. C. Brown, "Electronic and mechanical improvement of the receiving terminal of a free-space microwave power transmission system," Raytheon Company, Wayland, MA, Tech. Report PT-4964, NASA Report No. CR-135194, Aug. 1977.

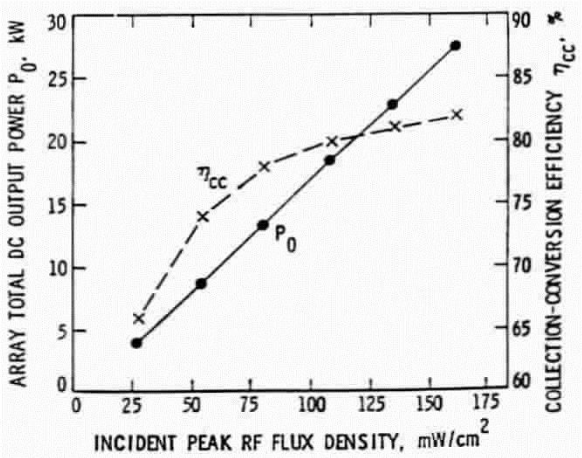
JPL - Raytheon Goldstone Experiment

Raytheon

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



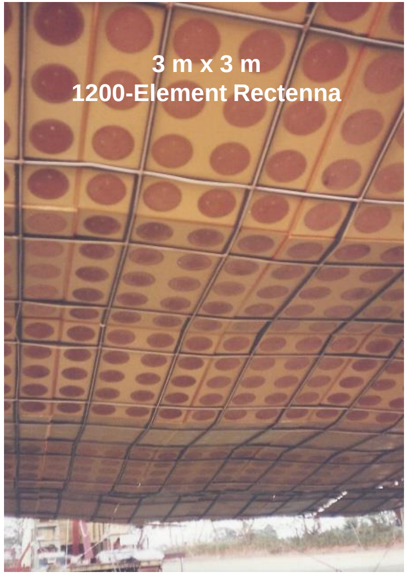


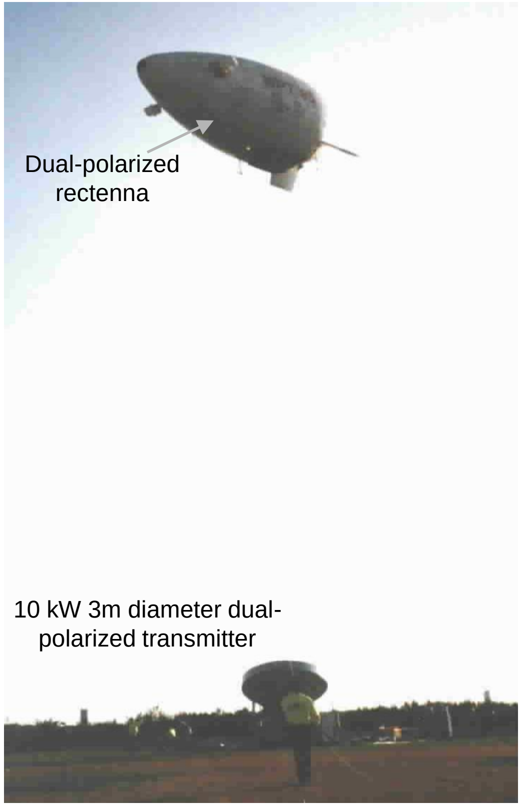


"Reception-conversion subsystem (RXCV) for microwave power transmission system, final report," Raytheon Company, Sudbury, MA, Tech. Report No. ER75-4386, JPL Contract No. 953968, NASA Contract No. NAS 7-100, Sept. 1975

Japanese ETHER Project

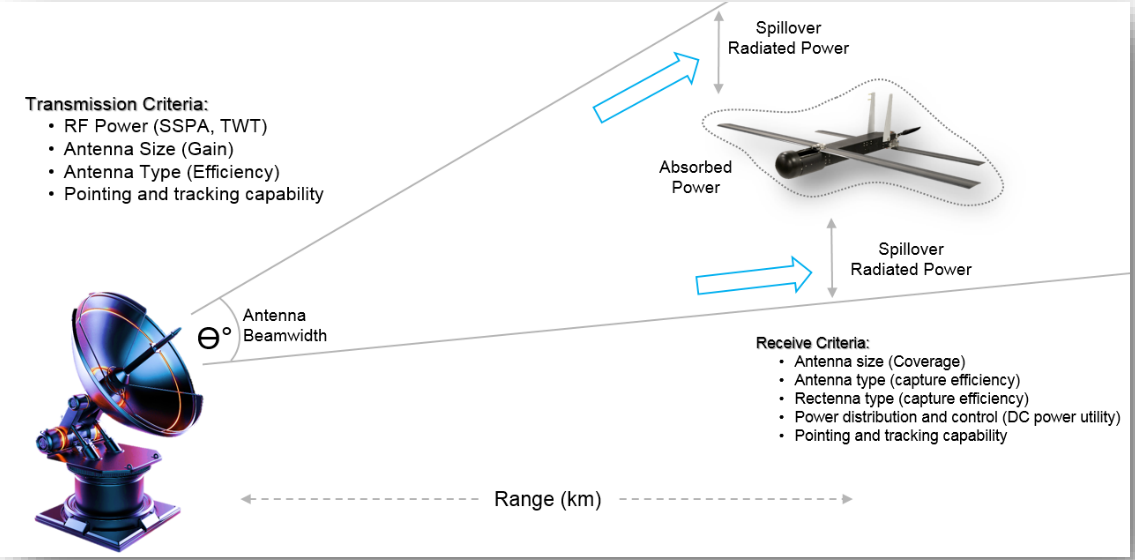
- 1995: Japan's Energy Transmission to a High altitude long endurance airship ExpeRiment (ETHER) program powered a blimp at 2.45 GHz
  - Flew 3-4 minutes at 50 m altitude, precursor to a 70,000 ft altitude airship





RF WPT System Architectures Tradeoffs

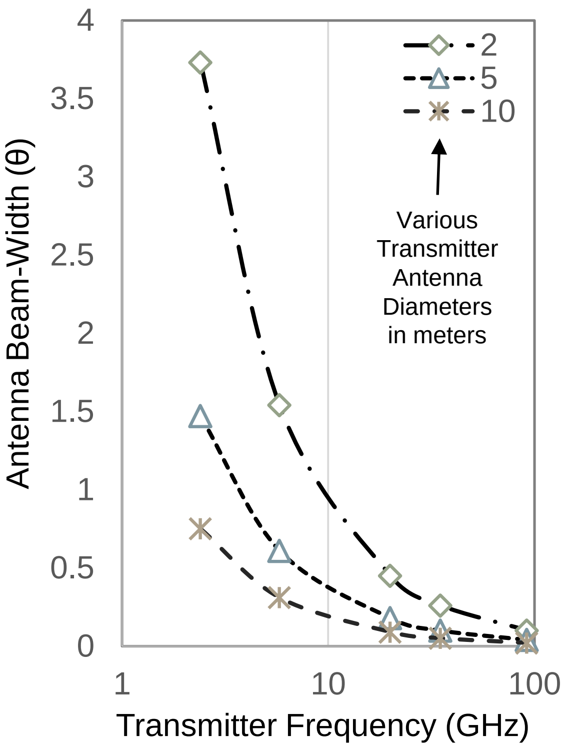
- Compare the same metrics for various frequency of operation to understand the trade-offs



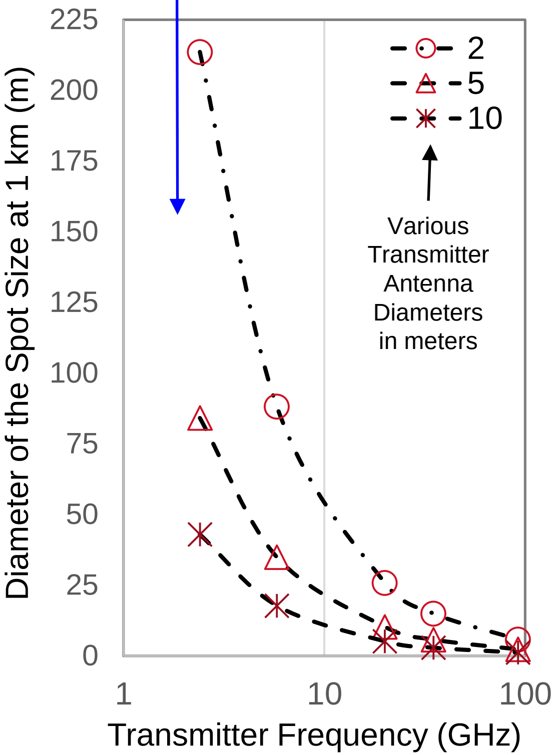
RF WPT Specs	Value
Frequency	2.4, 5.8, 20, 30, 92 GHz
Transmitter Power	100 kW
Transmitter Antenna Size	2m, 5m, 10m in diameter
Receive Antenna Size	1m
Range	1 km
Atmospheric loss	-0.19 dB/km worst case for all (92 GHz)
Beam-width, Area Coverage at Range, Antenna Gain	To be calculated

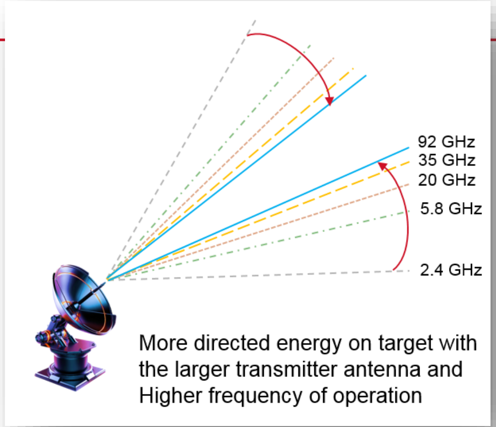
Transmitter Beam width is a Key Parameter for WPT applications

Raytheon



As the Aperture Size is increased the spot Size shrinks



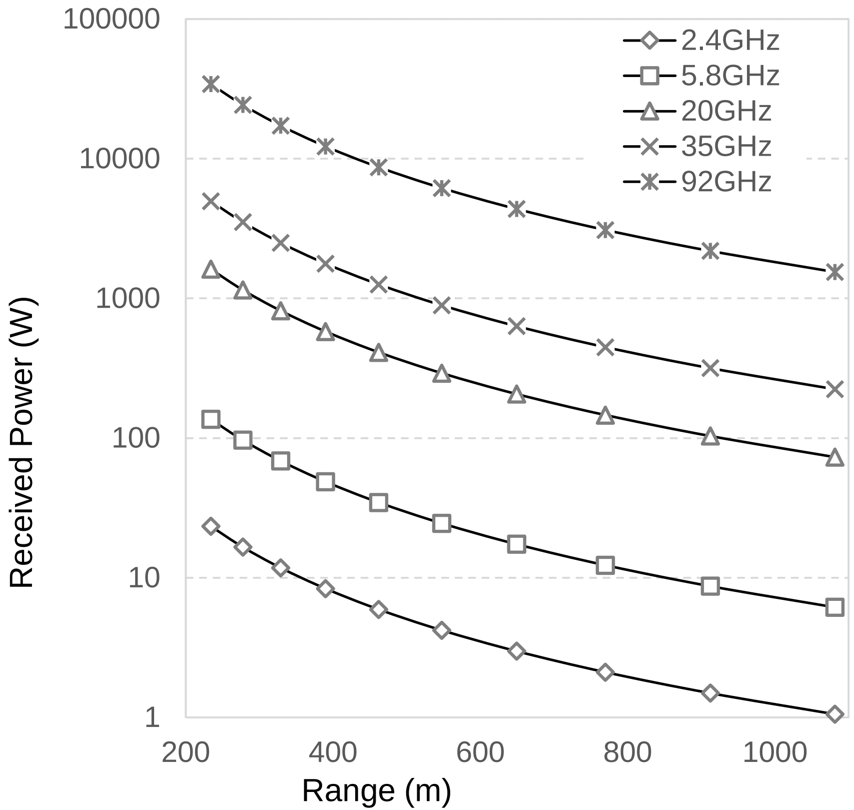


TX Aperture Diameter (m)	Freq (GHz)	Diameter of Area Covered @1km (m)
2	2.4	213.5936
2	5.8	88.1664
2	20	25.748
2	35	14.8912
2	92	5.74

TX Apertu	Freq (GHz)	Beam width (deg)
2	2.4	3.73
2	5.8	1.54
2	20	0.45
2	35	0.26
2	92	0.1

As the frequency is increased the spot Size shrinks

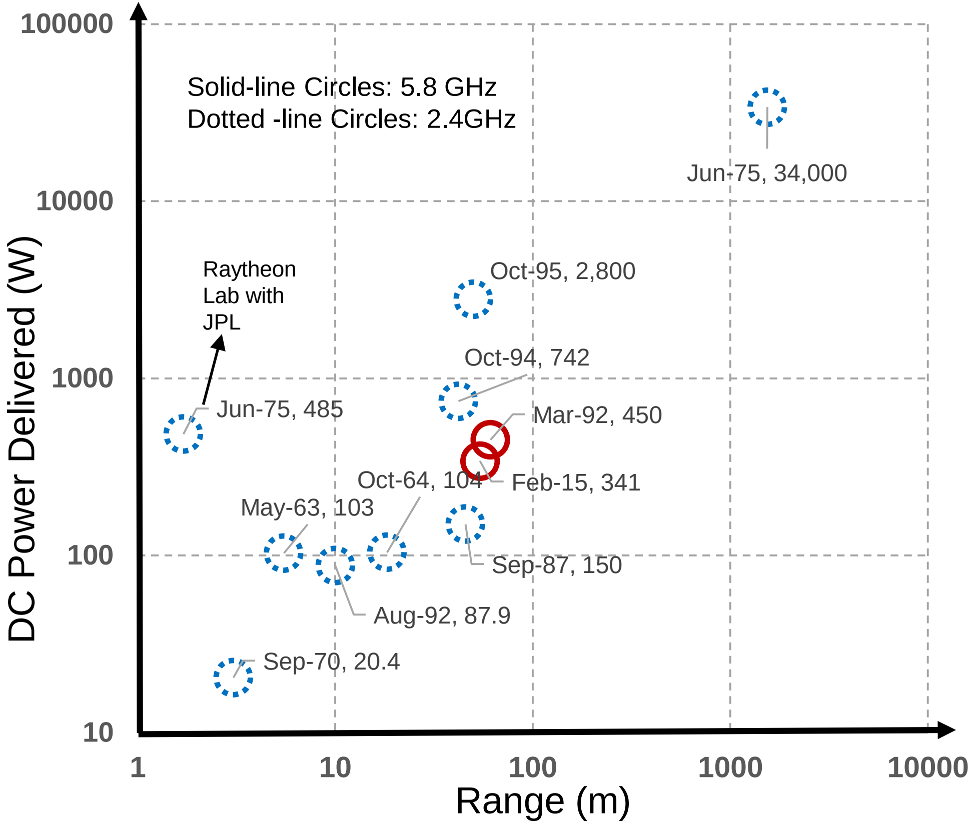
Beamed Power Received at Range

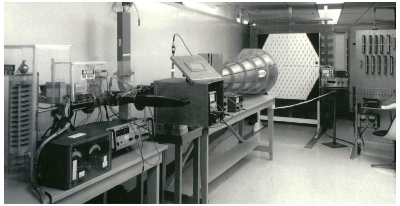


- Millimeter wave operation reduces the free-space path loss compared to other RF modalities
- Other important trade-offs are :
  - Component availability
  - Regulatory limitations
  - Safety concerns

The higher the frequency of operation the smaller the receive antenna and the higher the received power

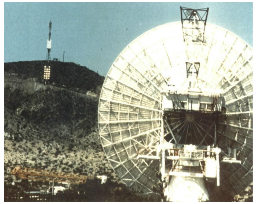
RF Based Wireless Power Beaming Demonstrations to Date





Raytheon Lab
Most efficient= 48% end to end

Japanese ETHER Airship



Goldstone JPL-Raytheon Experiment

Most Powerful DC Power-= 34 kW

Millimeter wave Wireless Power Transmission

High power Density at long Range

Raytheon

- MMW WPT provides more focused energy with smaller relative antennas
- Higher mmW power density (W/cm^2)
- Long range enables a variety of application (km)
- No interference to other systems
- Directional transmitter with electronic or mechanical steering
- All weather capability
- High power mmW transmitters have already been developed and demonstrated for directed energy applications
- Multi-modality capability can provide various CONOPs for low SWAP platforms
- Built-in safety based on substantial exposure studies

Solid State Based 7 kW Transmitter at 92 GHz

TWT Based 100 kW Transmitter at 92 GHz

6-8” high power, low SWAP directional rectennas can be built to efficiently convert the transmitter power into DC power

History of Active denial Transmitter Development for Personnel Repel

Tube Based Active Denial Systems

System 0 & 0+ (2000)

100 kW

System 1 (Circa 2004)

100 kW

System 2 (circa 2008)

100 kW

System 1R (Circa 2014-15)

100 kW

Solid State Active Denial Technology (SS-ADT) Capabilities

"7kW Skid-Plate" 2014

Gimbal Upgrade 2016

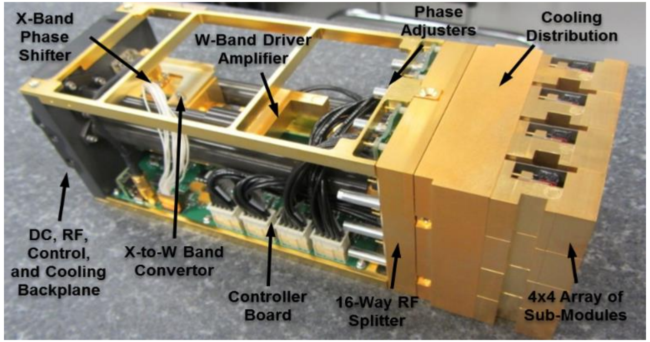
- Agile "Crew Serve" size
- Scalable range – Modular RF Source
- Electronic focusing and Beam Steering
- Fast power-up
- Fills Suppress, Move, Deny capability gaps against personnel

Leverage development of high power non-lethal repel transmitter sources to wirelessly provide usable power at stand-off distances

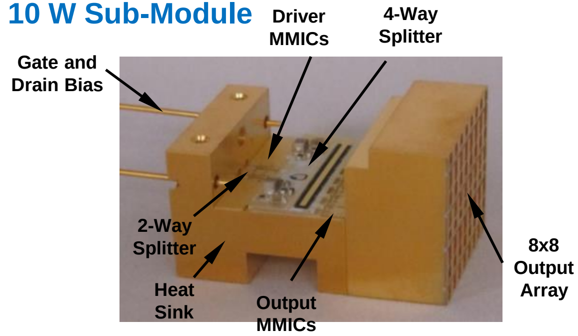
High Power Millimeter wave Scalable Transmitter

Raytheon

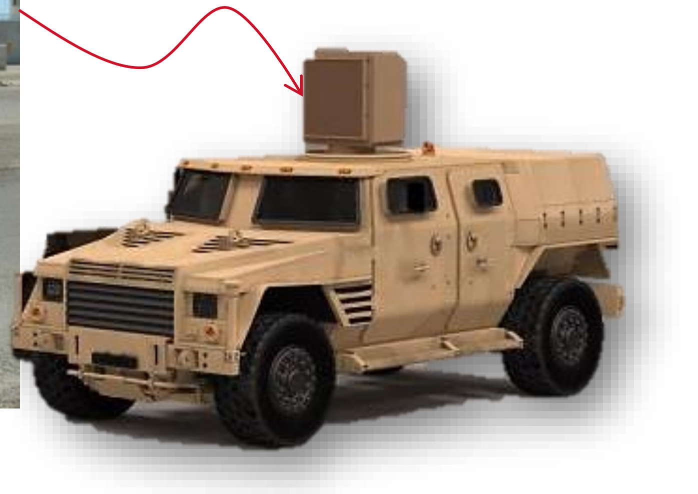
100 W Module (4x4 Submodules)



10 W Sub-Module



7000 W System (8x8 100W modules)

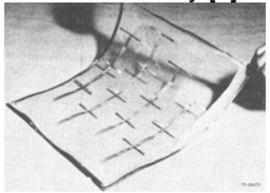


ADS system Modular 7KW tactical system is comprised of 8,192 1W+ GaN Output MMICs, 1024 7W+ Sub-Modules and 64 100W+ Modules

Printed Circuit Rectenna Array Performance Comparison

	Rectenna Type	Operating Frequency (GHz)	Measured Peak Conversion Efficiency	Peak Output Power per Element (W dc)	Polarization	Mass to dc Output Power Ratio (W/kg)	Specific Mass (kg/m^2)
A	Printed dipole	2.45	85%	5	Linear	4000	0.25
B	Circular patch	2.45	81%	5	Dual	263	2.5
C	Printed dipole	2.45	70%	1	Dual	-	-
D	Printed Dual Rhombic	5.61	78%	0.096	Circular	-	-
E	Square patch	8.51	52%	0.065	Dual	-	-

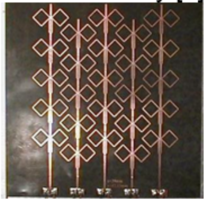
A: Bill Brown's thin-film rectenna array [1]



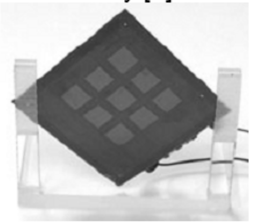
B: Japanese ETHER rectenna array [1]

C: Canadian SHARP rectenna array [1]

D: Texas A&M rectenna array [2]

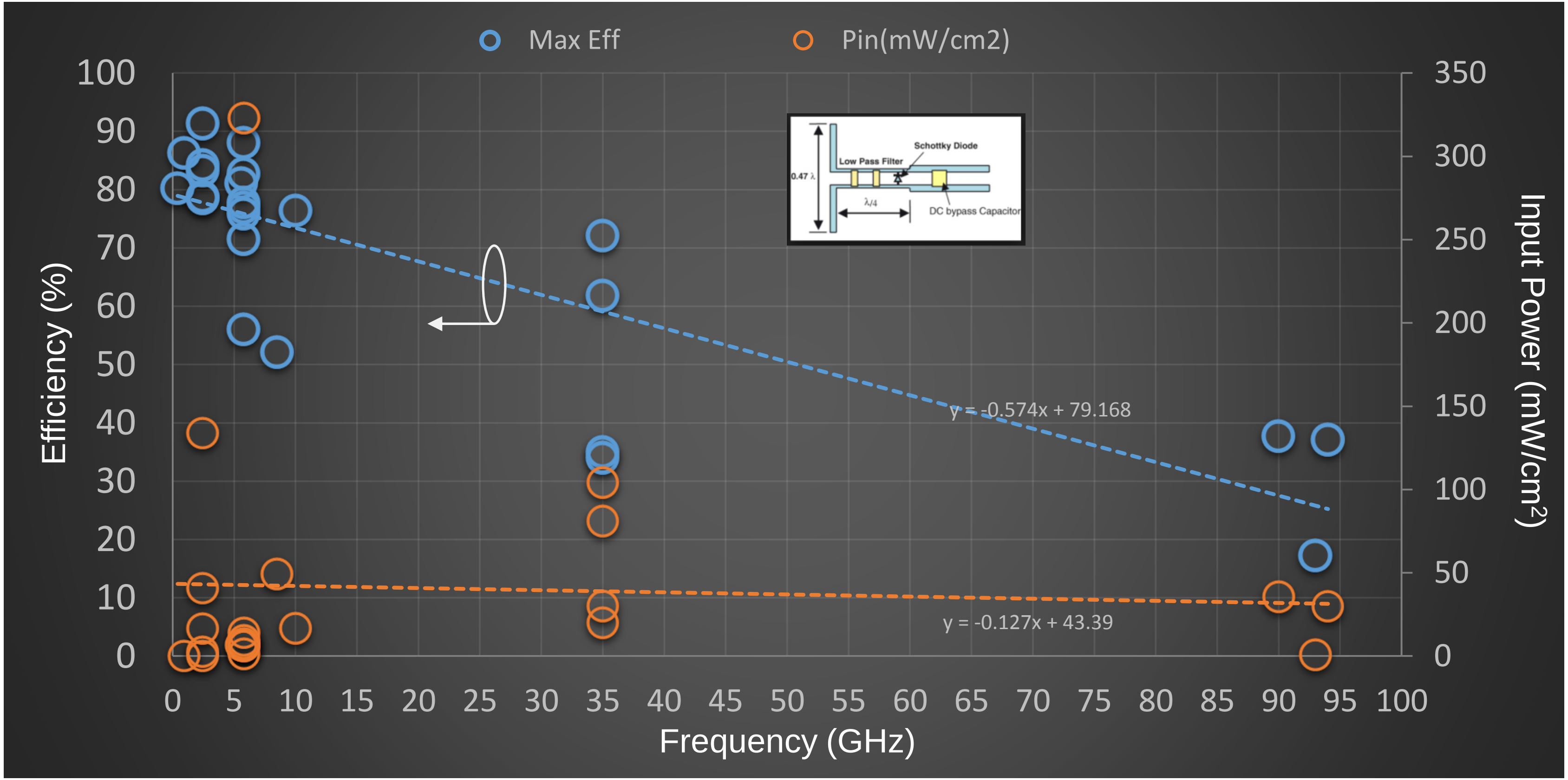


E: JPL rectenna array [3]



[1] J.O. McSpadden and J.C. Mankins, "Space solar power programs and microwave wireless power transmission technology," IEEE Microwave Magazine, vol. 3, no. 4, pp. 46-57, Dec. 2002.
[2] B. Strassner and K. Chang, "Highly efficient C-band circularly polarized rectifying antenna array for wireless power transmission," IEEE Trans. Antennas and Propagation, vol. 51, no. 6, pp. 1347-1356, June 2003.
[3] S.H. Choi, K.D. Song, W. Golembiewskii, S.-H. Chu and G.C. King, "Microwave power for smart material actuators," Smart Materials and Structures, vol. 13, pp. 38-48, 2004.

Rectenna Performance from 1950s to Now



Rectenna Design at mmW Requires Careful Analysis of the Circuit elements (Function versus Insertion Loss)

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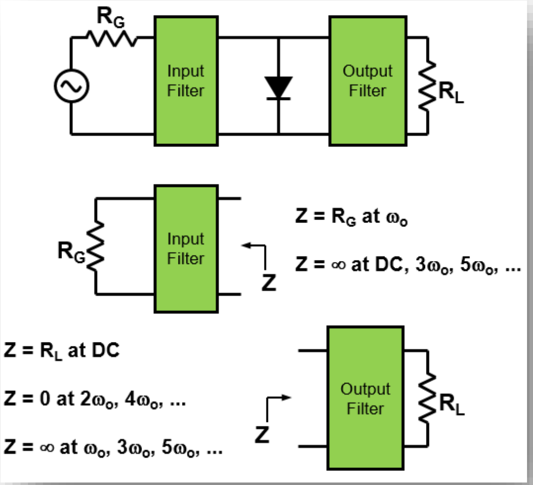
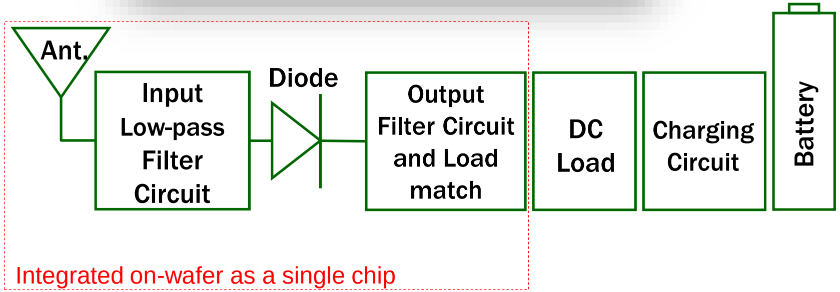
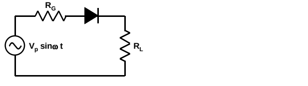
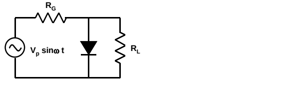
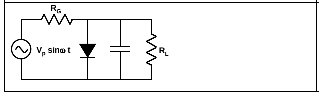
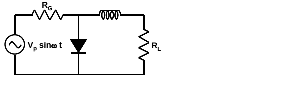
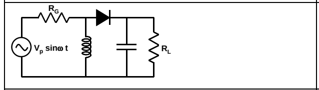
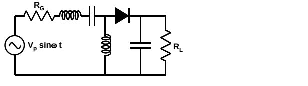
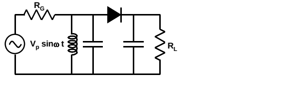
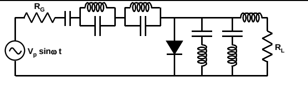
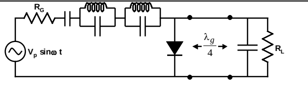
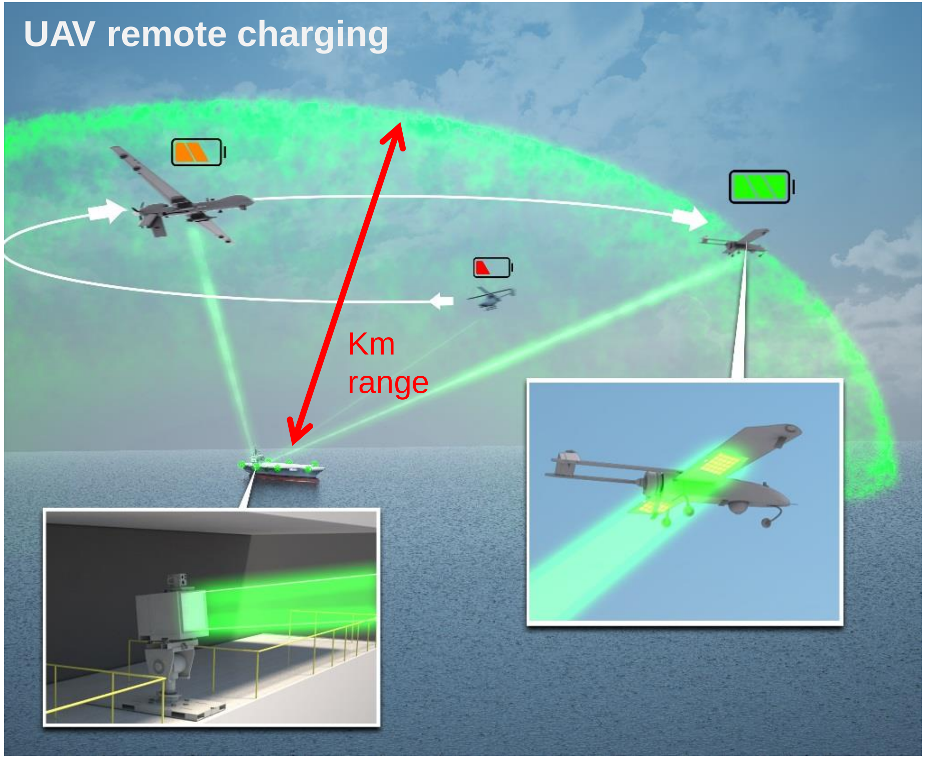




Rectifying Circuit	Maximum Efficiency	R_G and R_L Relationship for Maximum Efficiency
	20.3%	$R_L = R_G$
	20.3%	$R_L = R_G$
	46.1%	$R_L = 2.695\ R_G$
	46.1%	$R_L = R_G/2.695$
	81.1%	$R_L = R_G$
	100%	$R_L = R_G/2$
	100%	$R_L = 2\ R_G$
	100%	$R_L = \frac{\pi^2}{8} R_G$
	100%	$R_L = \frac{\pi^2}{8} R_G$

Ground-to-Air power Transmission Example

Raytheon



- Small area Rectennas on Air platforms with the directional transmitters on Ground or ship
- Careful Analysis of the WPT system needs to be conducted to define the important metrics for each CONOP
  - Transmitter Power density
  - Receiver area, efficiency
  - Time on target
  - Trade-off of wireless power and storage versus use

Conclusion

- Millimeter wave frequency range provides key advantages for Wireless power beaming through:
  - Directed focused energy
  - Long range
  - Scalable transmitted power 7kW-100kW and beyond
  - Efficient Receiver technology
  - Low cost / low weight / large format receiver
  - Safe operation