15 Critical Measurements for Power Beaming Links

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Spectrum Allocation is a Critical Prerequisite for Microwave Power Beaming For Space Solar

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Subsystems of a Solar Power Satellite System

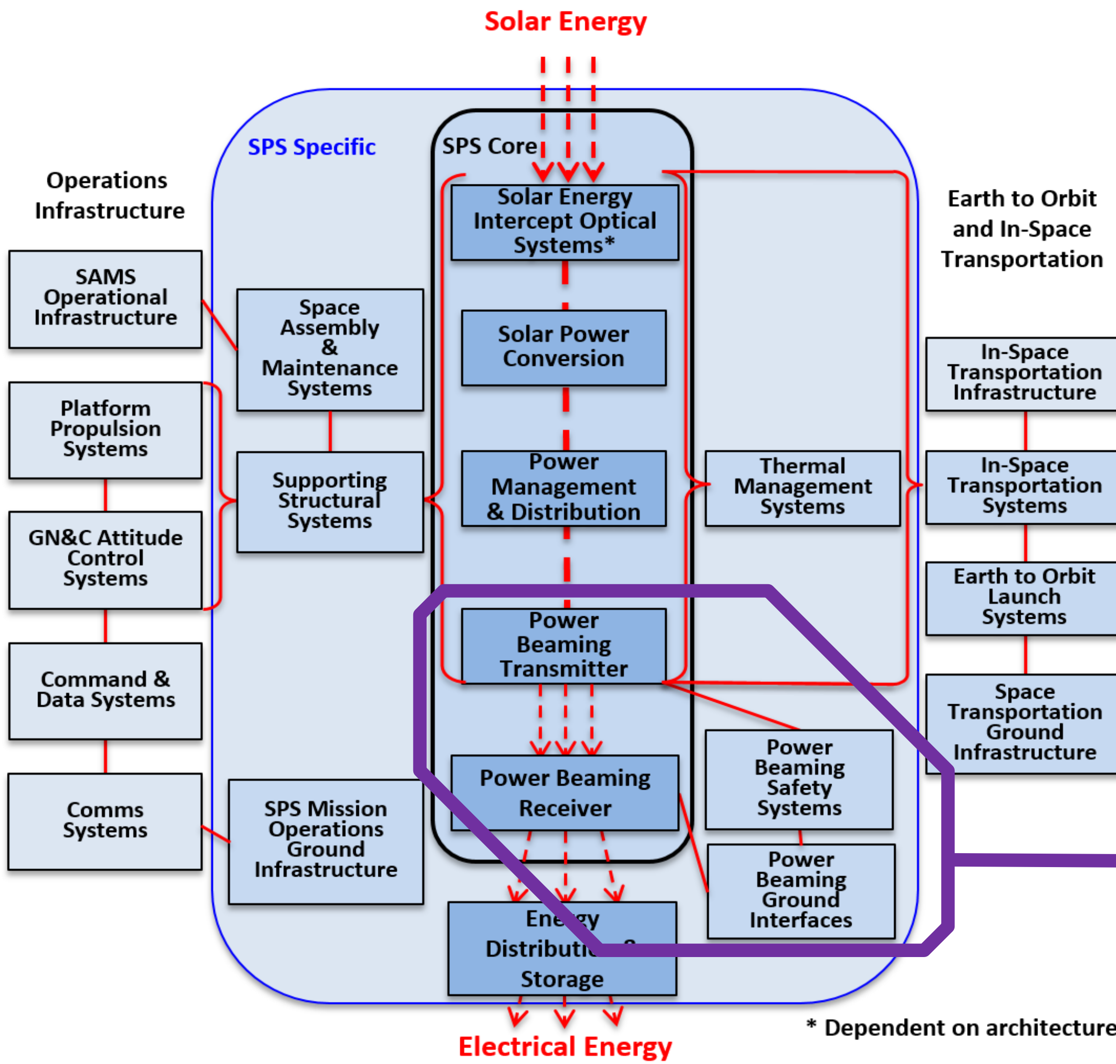
Abbreviations:

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



If these can't be effectively implemented, there is no system

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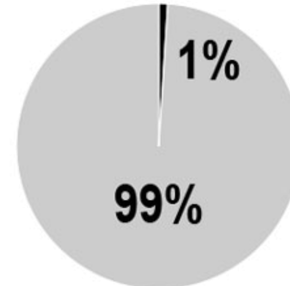
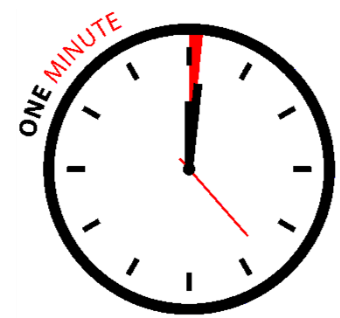
An Arbitrary Human-Scale Definition of "Power Beaming"

- 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**



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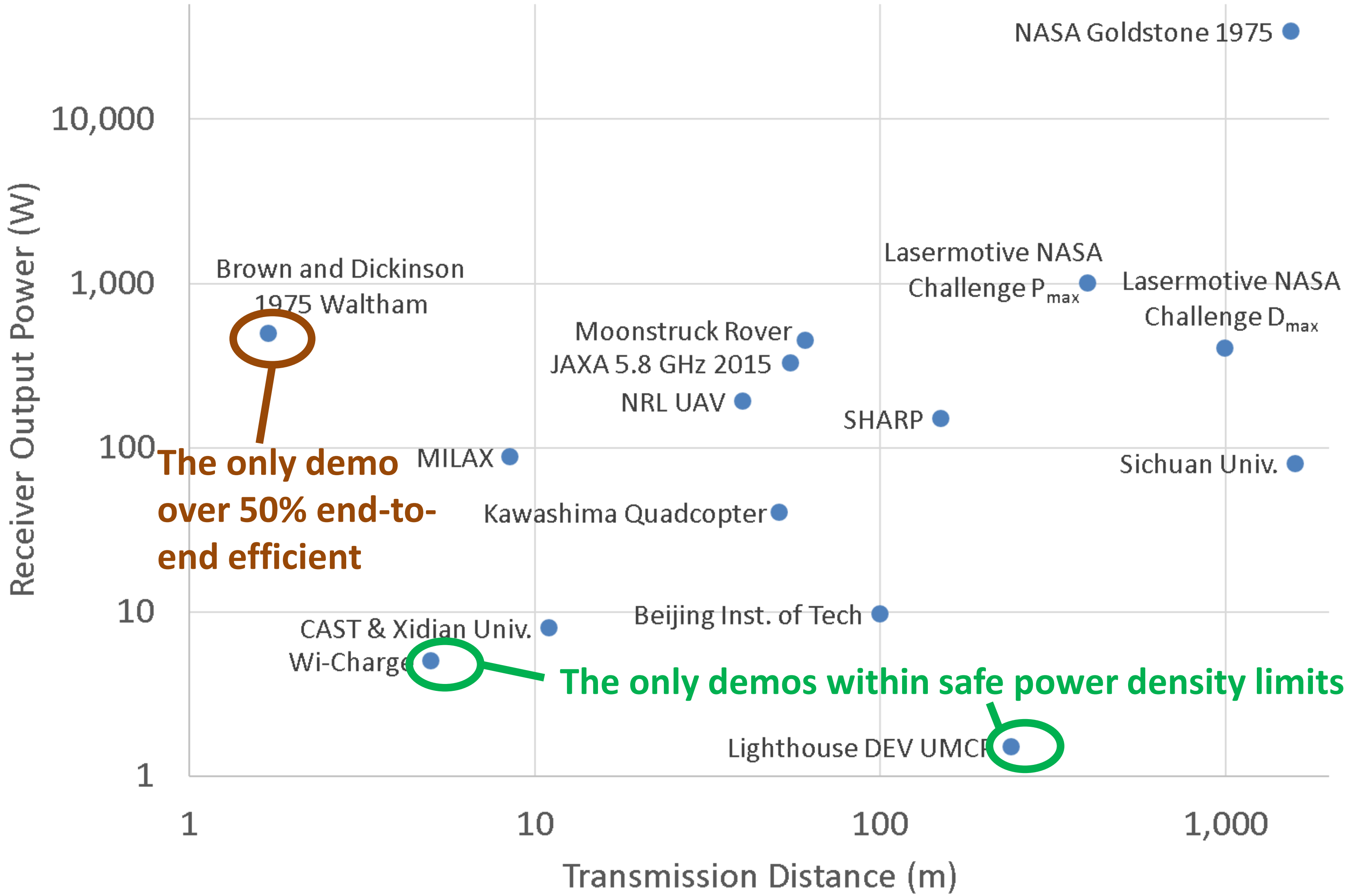
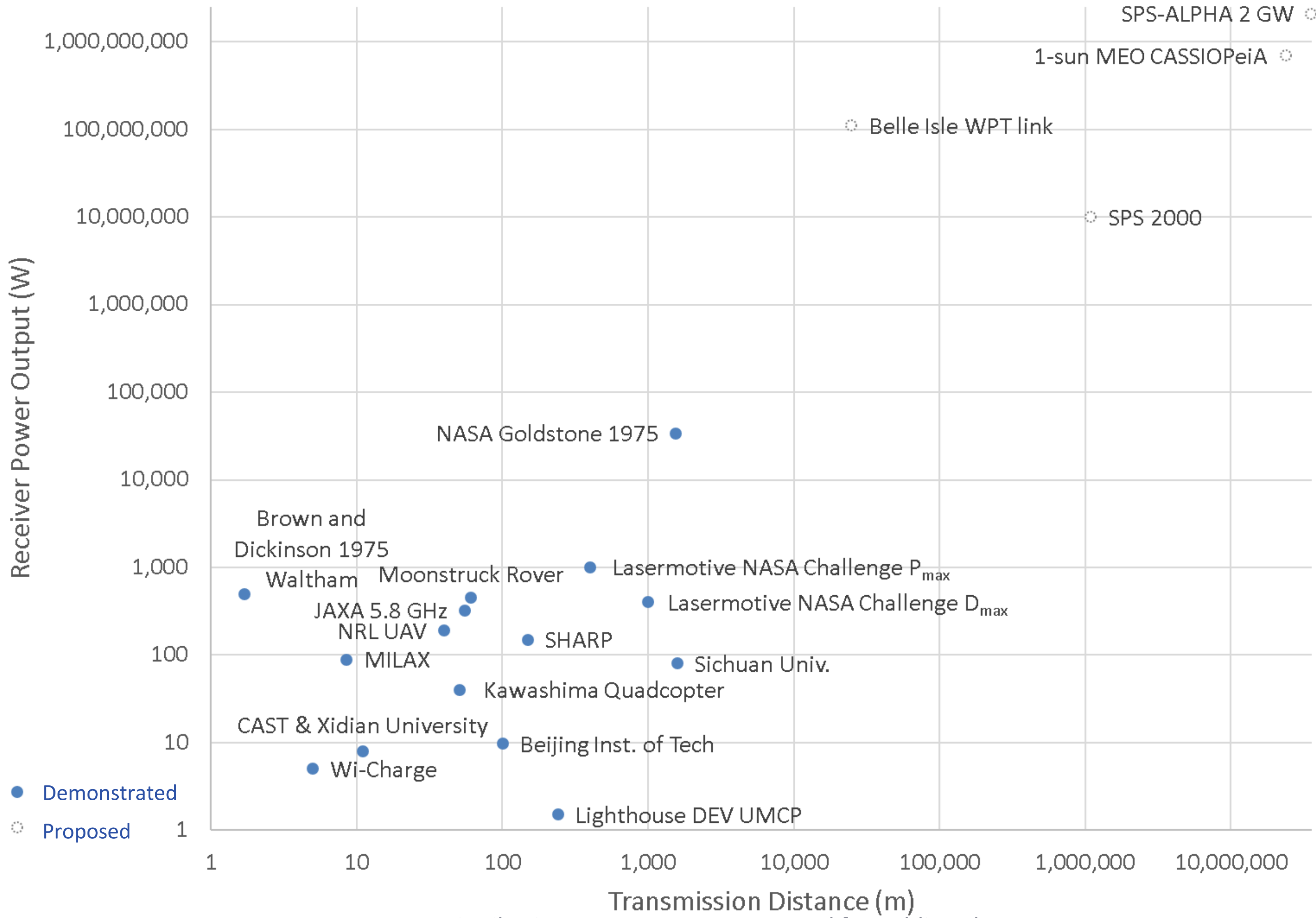
Receiver Power Output vs. Transmission Distance



Receiver Power Output vs. Transmission Distance



Power Beaming Measurements

- Historically, power beaming link documentation has not always included all the pertinent information for meaningful comparisons

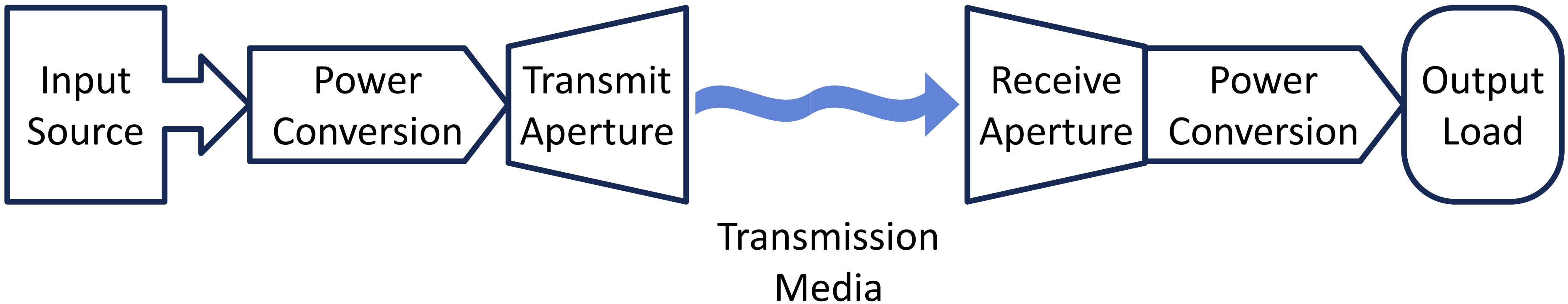
- The 15 critical measurements outlined herein form a basis for allowing for useful comparisons between power beaming systems

- Many derived quantities of interest can be calculated from the 15 measurements

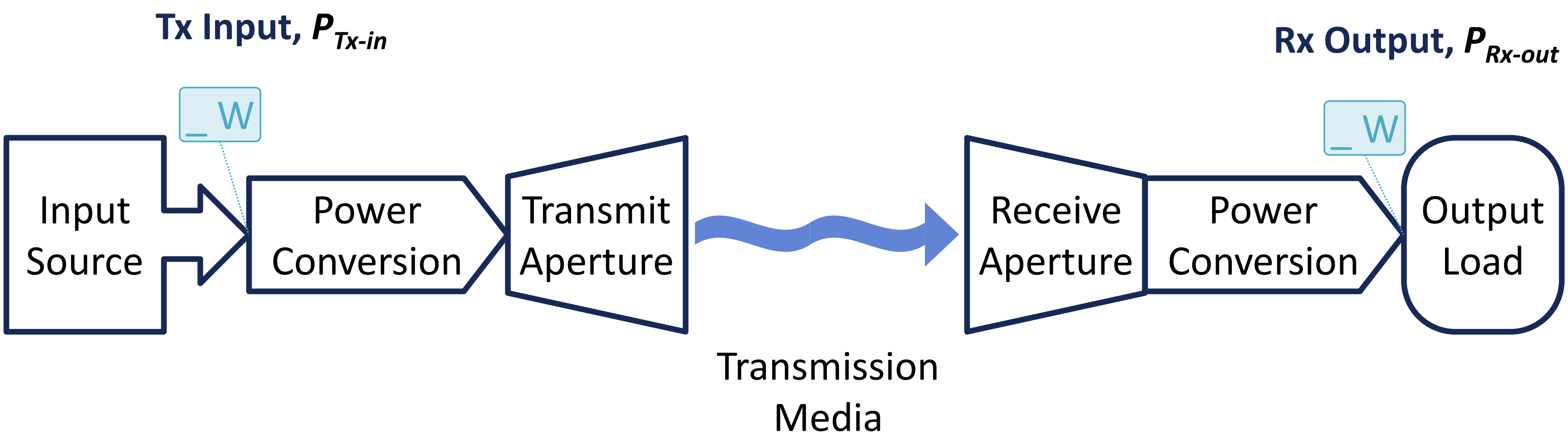
- Other information may also be of interest: parameters related to cost, What, Where, When, Who, Why, How, etc.

- Guides for making accurate measurements to account for uncertainty and other factors:
  - “Introduction to Measurements & Error Analysis” https://users.physics.unc.edu/~deardorf/uncertainty/UNCguide.html
  - “ISO Standards Catalog 17.020 - Metrology and measurement in general” https://www.iso.org/ics/17.020/x/

Power Beaming Block Diagram

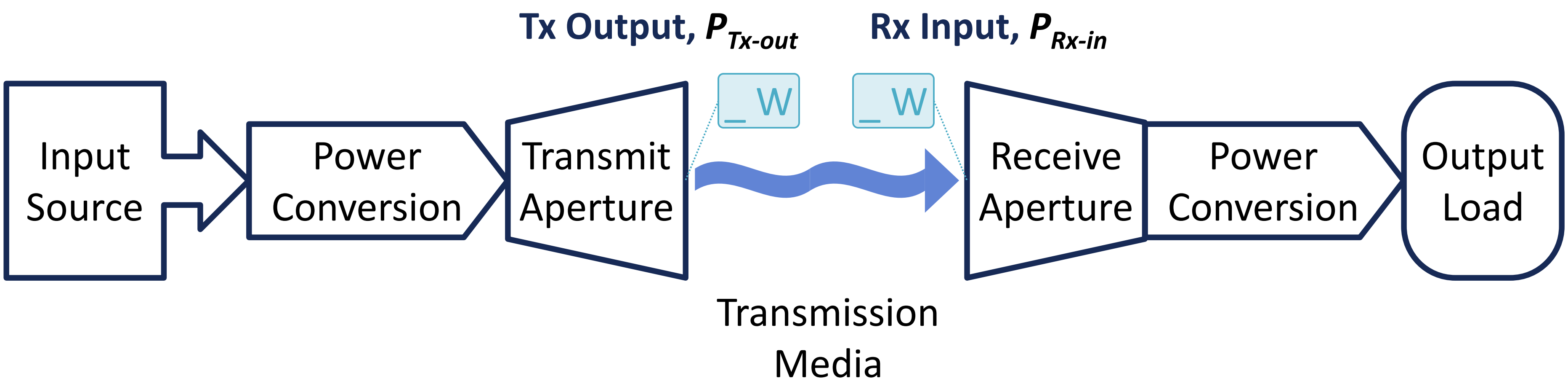


System Power Input and Output



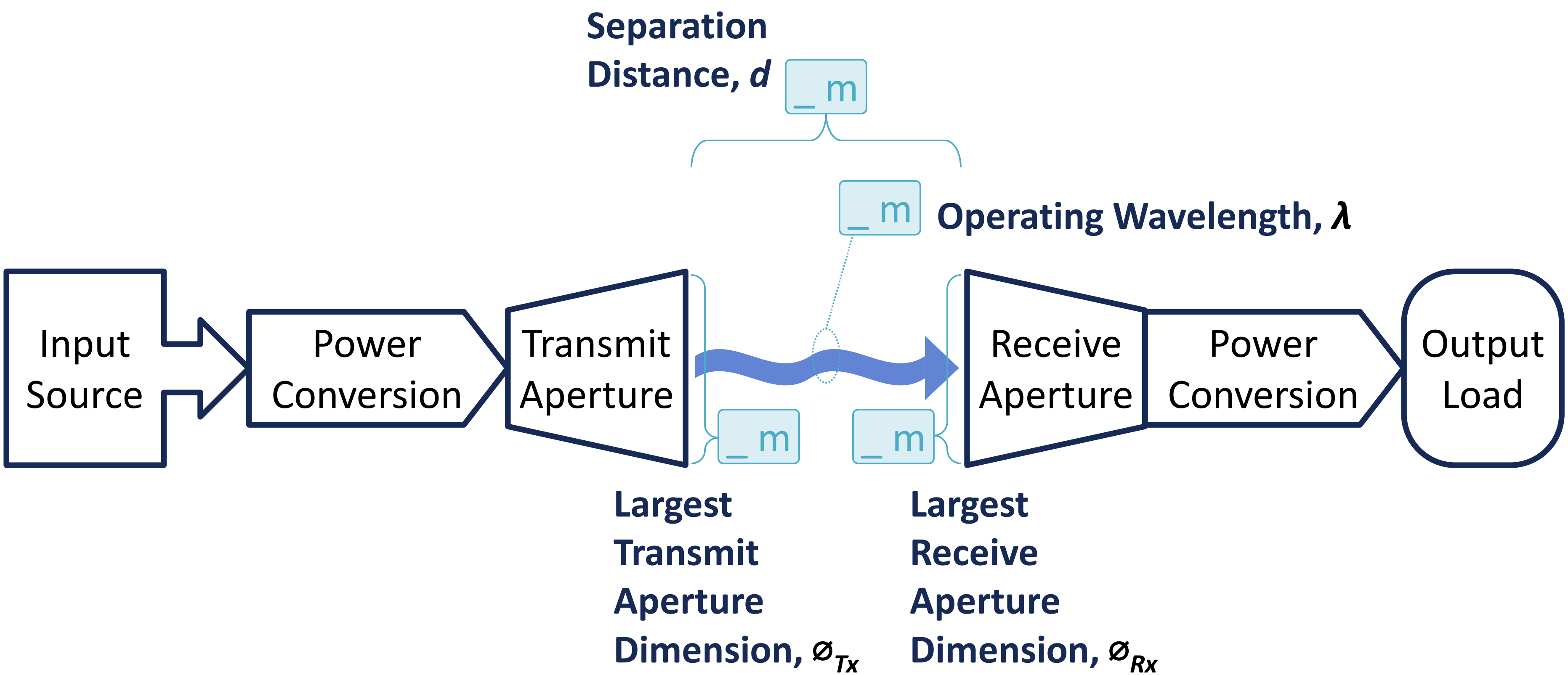
Input and output power of the system, measured in Watts. Mean, minimum, and maximum values may be appropriate to measure also.

Transmitted and Received Power



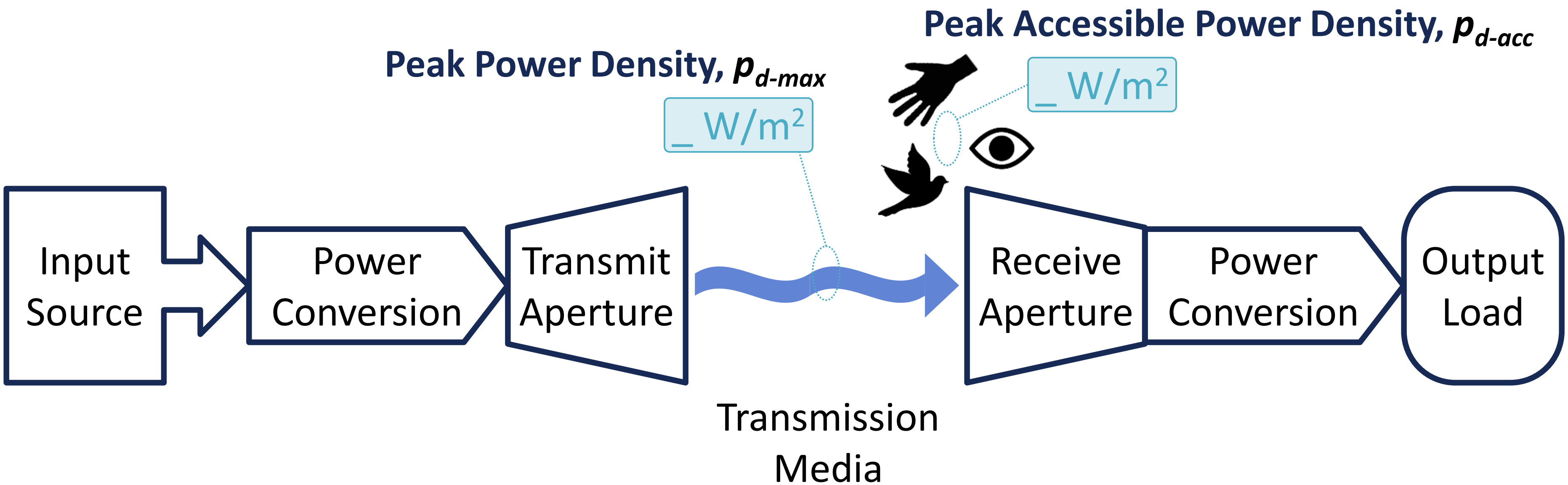
Power transmitted and received. The measurements will show loss in the link due the transmission media factors and low beam collection efficiency.

Separation Distance, Wavelength, and Largest Aperture Dimensions



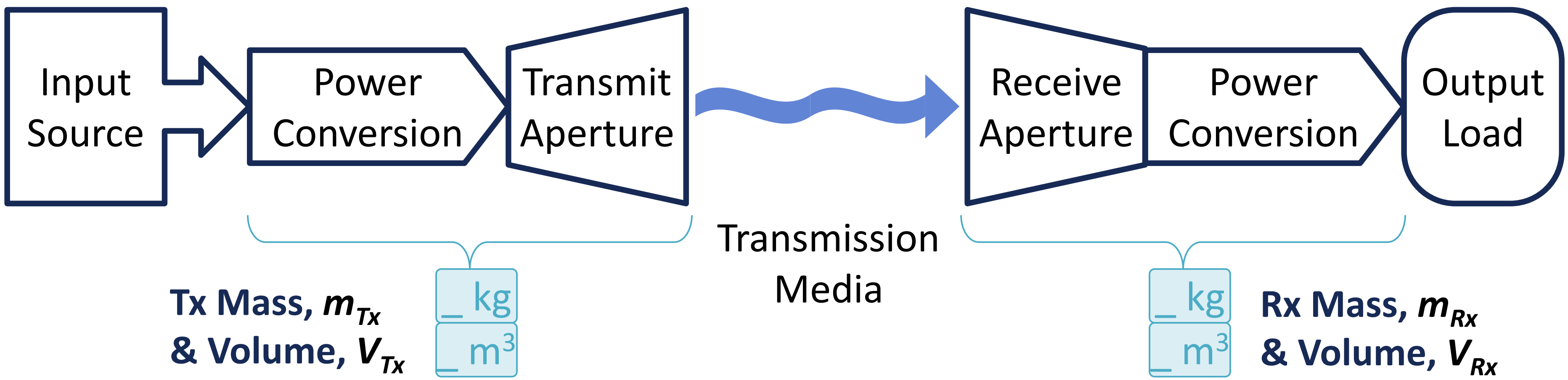
These linear measurements define the expected Beam Collection Efficiency (BCE), assuming no losses due to pointing or polarization mismatches.

Power Densities



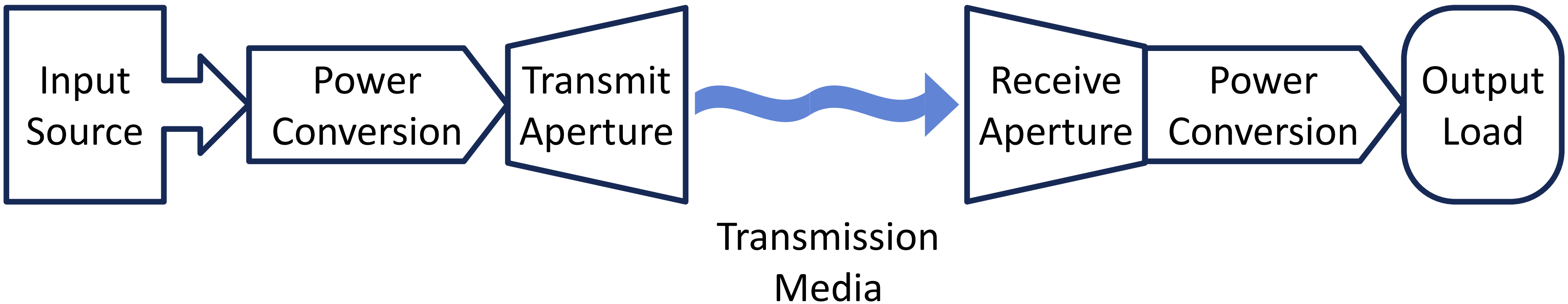
The peak power density along the beam gives an indication of the likelihood of effects resulting from power dissipation in the medium. The peak accessible power density (to people, animals, etc.) indicates if there may be a safety risk.

Transmitter and Receiver Size and Mass



For nearly every application, there will be mass and volume constraints on either the transmitter, receiver, or both.

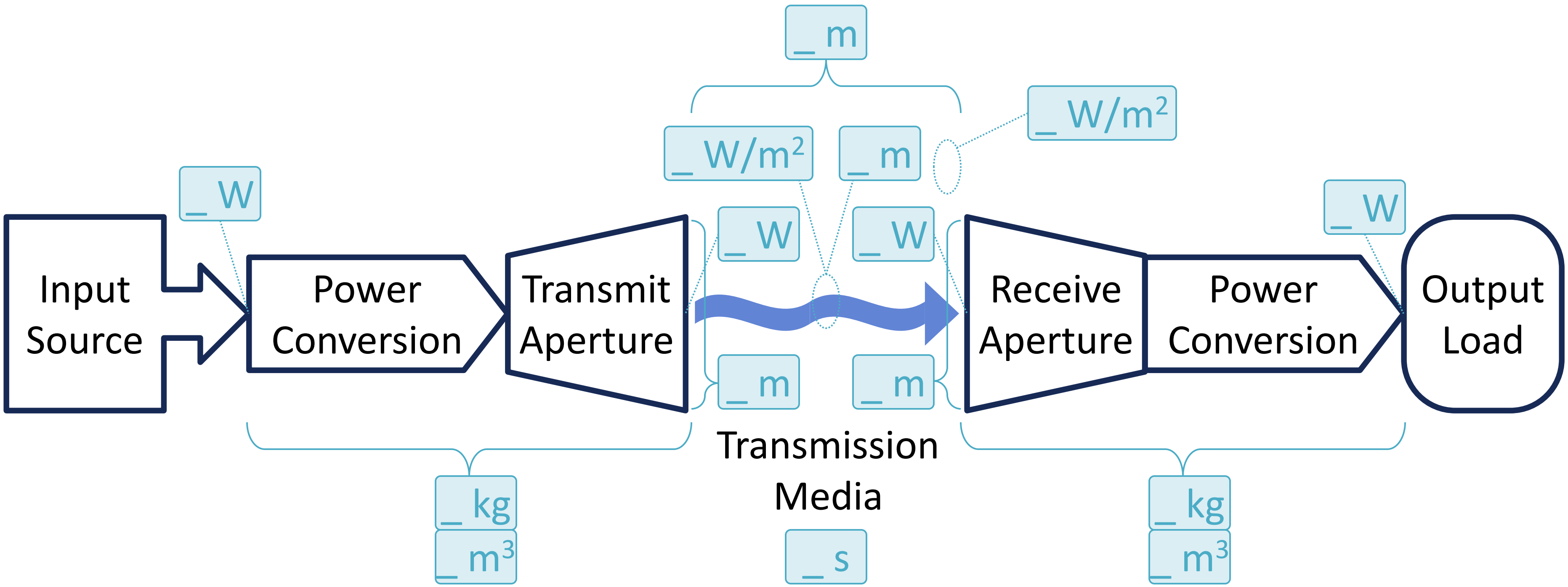
Duration of Link Operation



Link Operating Duration, *t* _ s

The time that the link can be active may be constrained by thermal management limitations or other factors.

Critical Power Beaming Measurements



Power Beaming Link Measurement Summary

Power Beaming Link Measurement Summary		
Parameter	**Recorded Value**	**Description**
Date		The date the demonstration occurred. For multi-day demonstrations, the first day of operation.
Location		The location the demonstration occurred.
Title		A short, descriptive title to distinguish the demonstration from others
λ (m)		The wavelength corresponding to the frequency of operation (or operating frequency in Hz)
$\varnothing_{Tx}$ (m)		The largest dimension of the transmitter aperture, typically the diameter
m_{Tx} (kg)		The mass of the transmitter, including power conversion elements and the transmit aperture
V_{Tx} (m^3)		The volume of the transmitter, including power conversion elements and the transmit aperture
$\varnothing_{Rx}$ (m)		The largest dimension of the receiver aperture, typically the diameter
m_{Rx} (kg)		The mass of the receiver, including power conversion elements and the transmit aperture
V_{Rx} (m^3)		The volume of the receiver, including power conversion elements and the transmit aperture
d (m)		The distance between the transmit and receive apertures
$P_{Tx\text{-}in}$ (W)		The input source power to the transmitter
$P_{Tx\text{-}out}$ (W)		The power output of the transmitter at the frequency of operation
$p_{d\text{-}max}$ (W/m^2)		The peak power density anywhere along the beam's path
$p_{d\text{-}acc}$ (W/m^2)		The peak power density accessible to people, animals, aircraft, etc.
$P_{Rx\text{-}in}$ (W)		The power incident on the receive aperture
$P_{Rx\text{-}out}$ (W)		The average power from the receiver to the output load during the demonstration
t (s)		The duration over which the power link was active
Add'l References		Additional data sources

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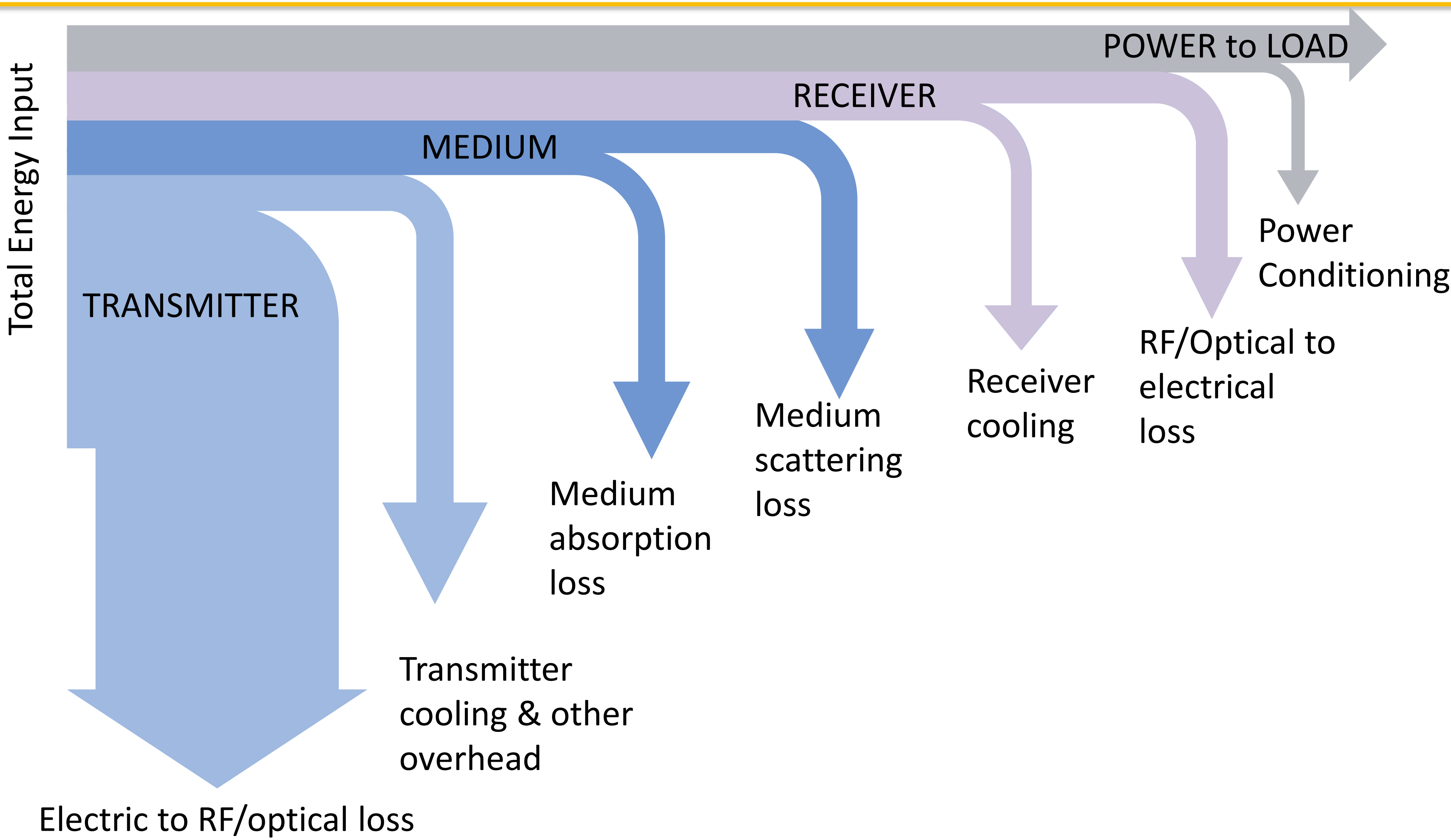
Notional "Sankey" Diagram Loss Depiction



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Key Concluding Points

1. Past power beaming demonstration reports have lacked key details

2. Making the 15 measurements described will allow for meaningful comparisons of future demonstrations and assessments of technology readiness

Thank You for Your Attention!

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Backup

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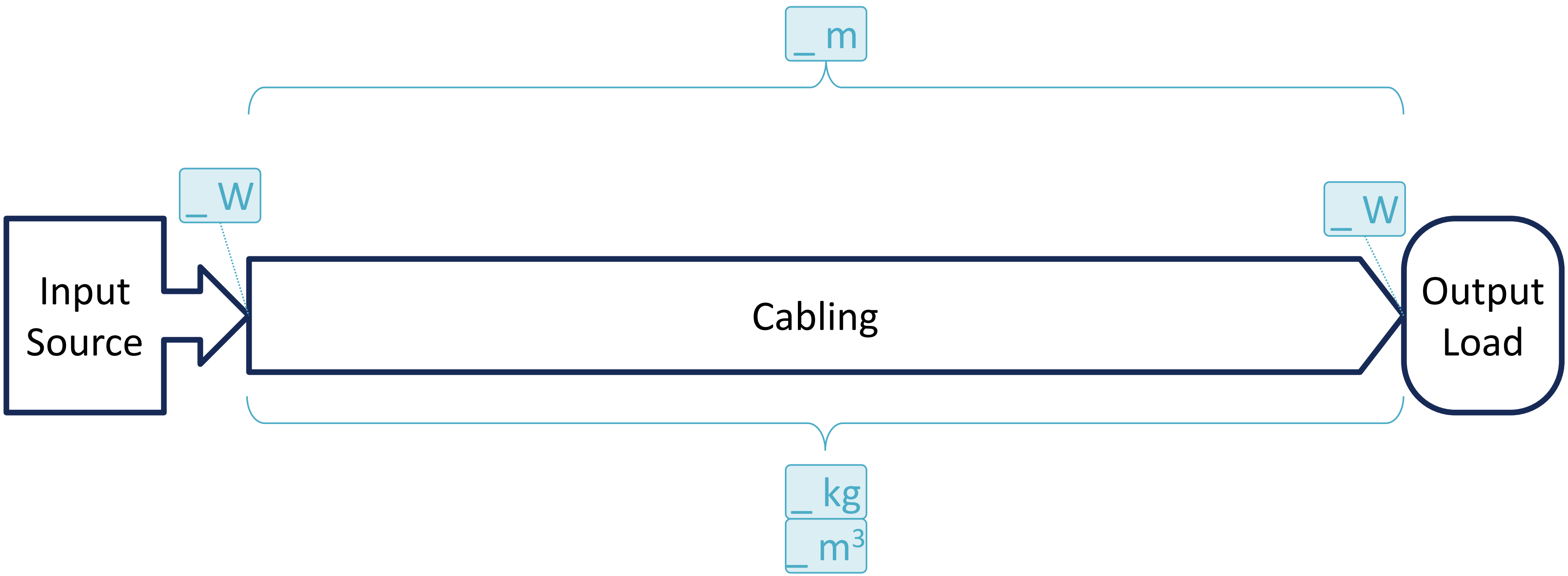
Metrics & Data for Power Beaming Demos & Systems

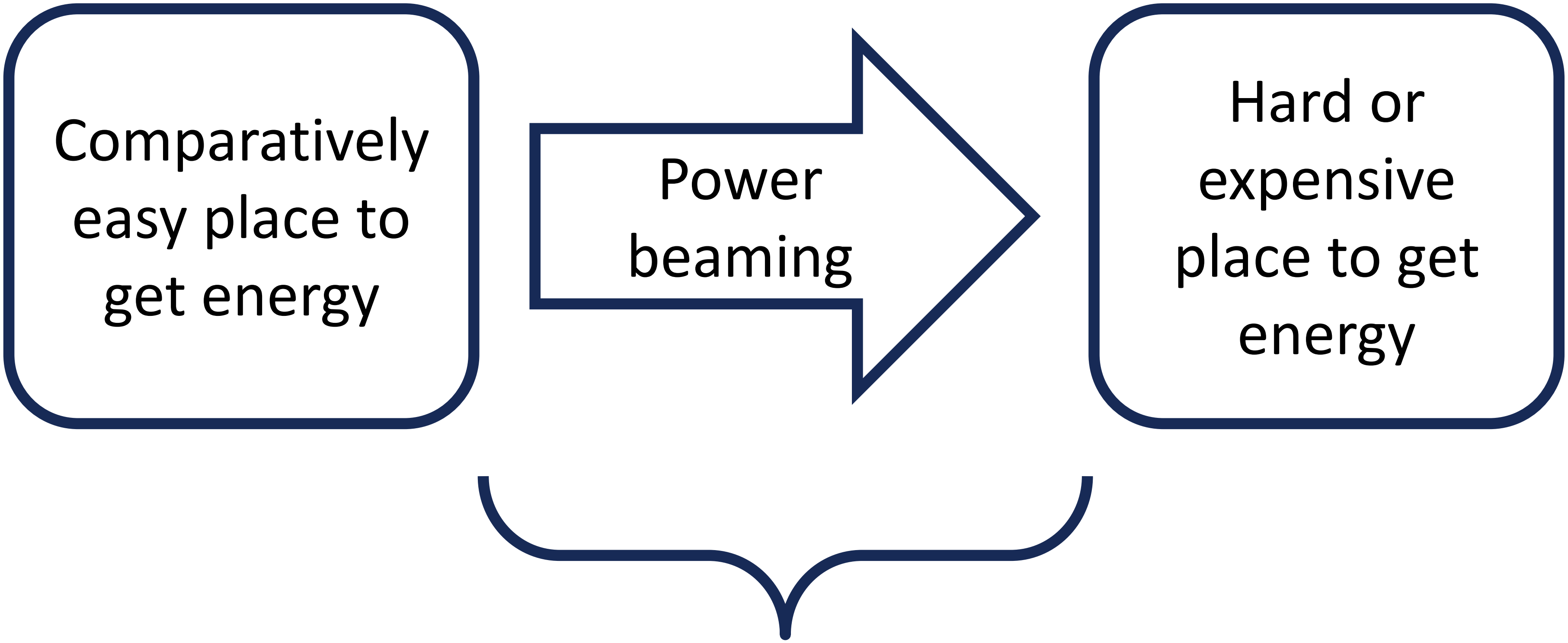
Parameter	Description
Date	The date the demonstration occurred. For multi-day demonstrations, the first day of operation.
Location	The location the demonstration occurred.
Title	A short, descriptive title to distinguish the demonstration from others
f (Hz)	The principal center frequency of operation for the demonstration
λ (m)	The wavelength corresponding to the frequency of operation
FWHM (Hz)	The full width at half maximum of the transmitter bandwidth
Tx ⌀ (m)	The largest dimension of the transmitter aperture, typically the diameter
Tx mass (kg)	The mass of the transmitter, including power conversion elements and the transmit aperture
Tx vol (m^3)	The volume of the transmitter, including power conversion elements and the transmit aperture
Rx ⌀ (m)	The largest dimension of the receiver aperture, typically the diameter
Rx mass (kg)	The mass of the receiver, including power conversion elements and the transmit aperture
Rx vol (m^3)	The volume of the receiver, including power conversion elements and the transmit aperture
Range (m)	The distance between the transmit and receive apertures
Max BE	The maximum beam efficiency theoretically achievable from the aperture areas, range, and operating frequency
Tx input (W)	The input source power to the transmitter
Tx power (W)	The power output of the transmitter at the frequency of operation
Tx eff	The percentage of input power that is transmitted
Tx pk (W/m^2)	The peak power density on the transmit aperture
Beam pk (W/m^2)	The peak power density along the beam's path
Rx pk (W/m^2)	The peak power density at the receive aperture
Rx power (W)	The power incident on the receive aperture
Rx output (W)	The average power from the receiver to the output load over the duration of the demonstration
Rx eff	The percentage of incident on the receive aperture that is sent to the output load
End-to-end eff	The percentage of power from the input source that is delivered to the output load
Duration (s)	The duration over which power was provided to the output load
Beam steering	Beam steering implemented, such as: none, electronic closed or open loop, mechanical closed or open loop
Safe [Y/N]	To answer "Y", the demo either did not exceed the applicable power density safety limits (IEEE, OSHA, ICNIRP, etc.), or an interlock system was implemented and tested that to prevent harm to personnel, animals, or property.
Cost ($)	Cost of the demonstration in then-year U.S. dollars
W cost ($/W)	Cost per watt delivered to to output load
Tag	The year the demonstration was performed suffixed with a letter to allow tagging of the demonstration on plots
Notes	Notes and aspects of interest related to the demonstration
Reference	Primary source for data
Add'l References	Additional data sources

Power Transmission Via Cabling



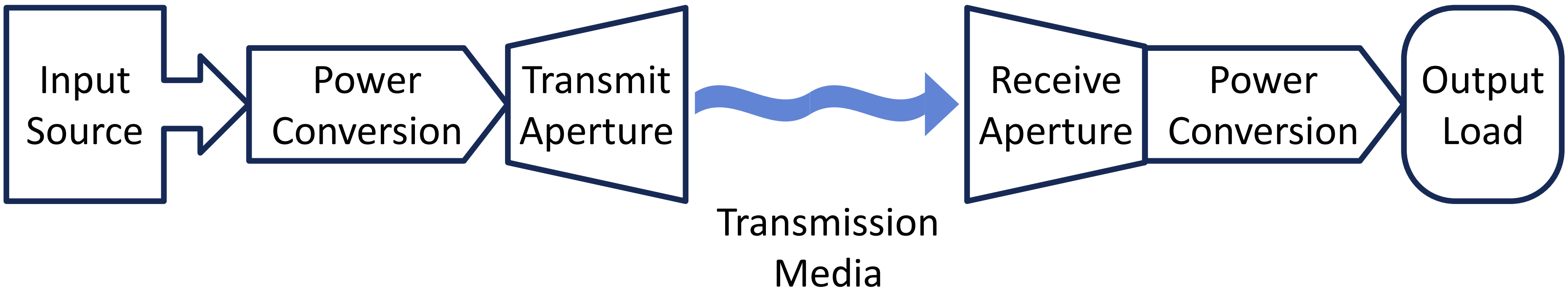
Input and output power of the system, measured in Watts. Mean, minimum, and maximum values may be appropriate to measure also.

What is Power Beaming, and Why Use It?



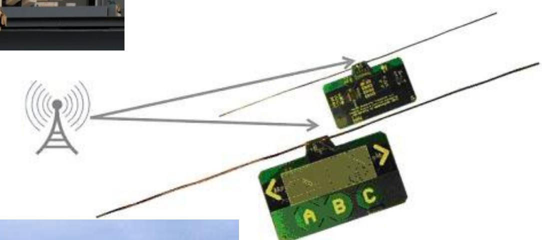
Separation ill-suited for a physical connection

Power Beaming Block Diagram



This Rules Out (Typically) …

- Communication links
  - Goal is to keep carrier above noise
- Directed energy
  - Goal is disrupting, disabling, or destroying 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 ↓
- Hazards (# birds fried)
  - Generally want to minimize ↓

Source: https://youtu.be/0WYu25SZKlY?t=36m

Electromagnetic Spectrum Regions of Interest for Power Beaming

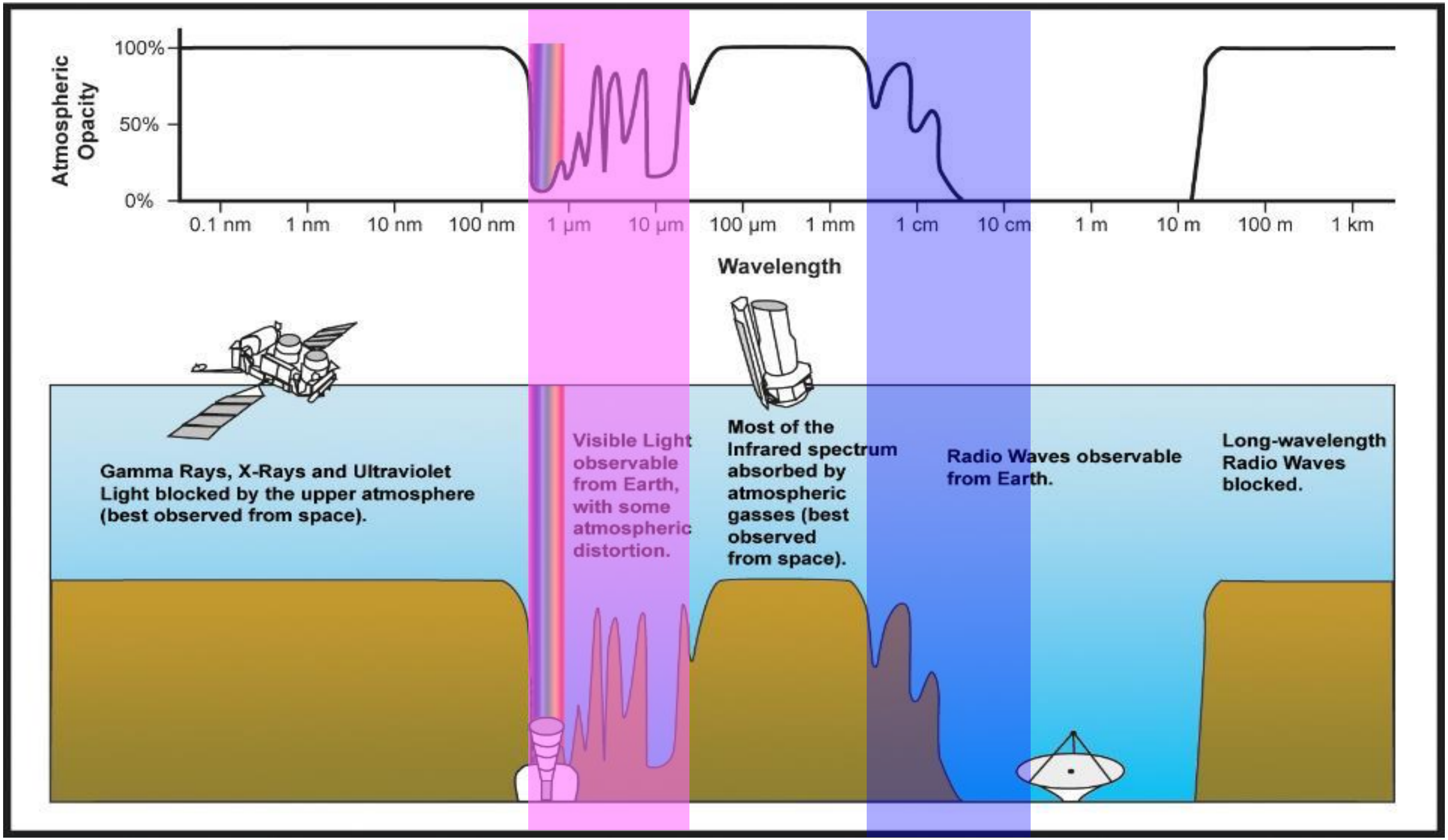


Figure adapted from https://img1.wikia.nocookie.net/__cb20071104233556/psychology/images/8/83/Atmospheric_electromagnetic_transmittance_or_opacity.jpg

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Power Beaming Technologies

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

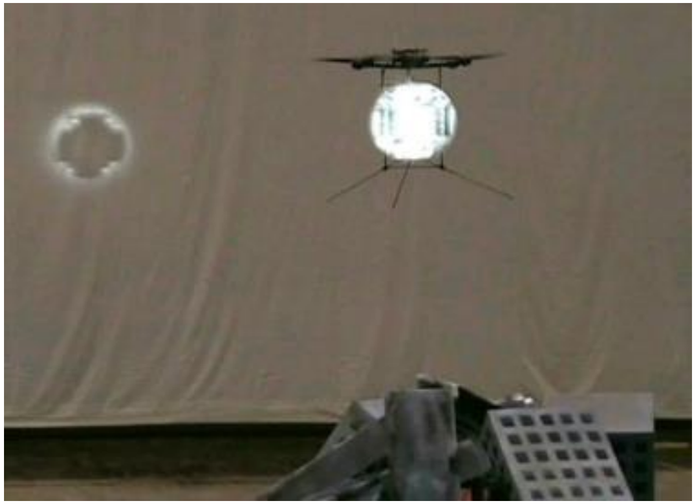
- mm-wave (~94 GHz)
  - Transmitter: gyrotron, solid state, etc.
  - Receiver: rectenna, heat engine

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

- Supporting tech
  - high altitude vehicles, aerostats, etc.

Selected Laser Power Beaming Demonstrations

EADS Astrium tracking laser to power rover (2003)

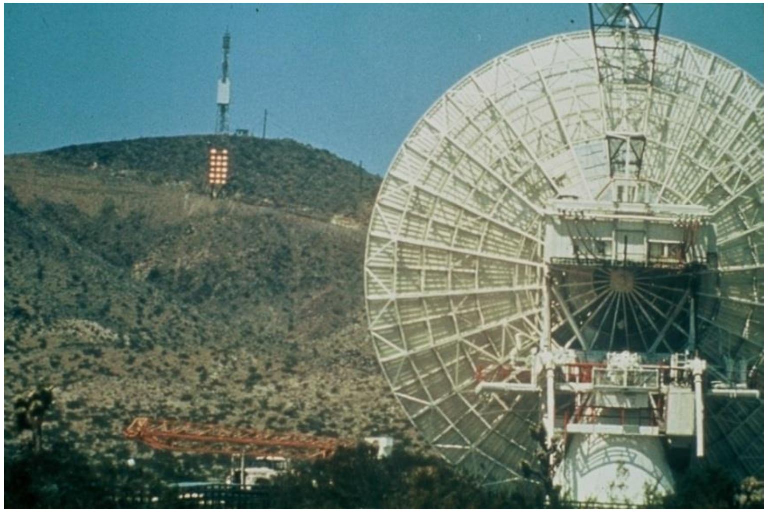


Kinki Univ. & Hamamatsu Photonics Inc. laser power to small helicopter (2007)

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

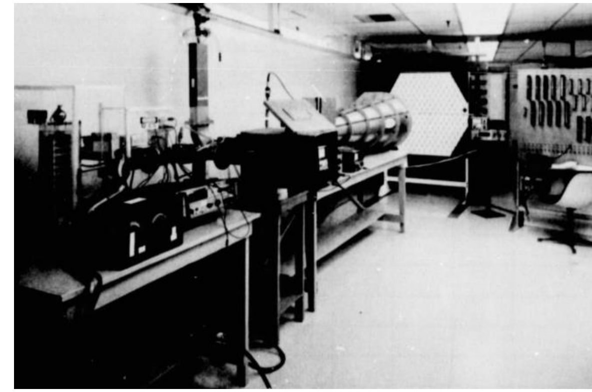
LaserMotive outdoor laser power to UAV (2012)

Selected Microwave Power Beaming Demonstrations

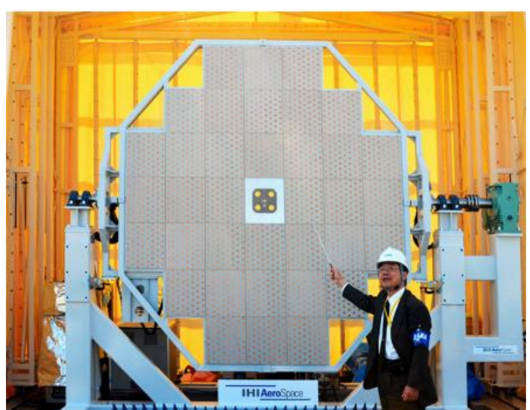


JPL-Raytheon Goldstone, 34 kW, 1.6 km (1975)

MILAX Kobe University (1992)

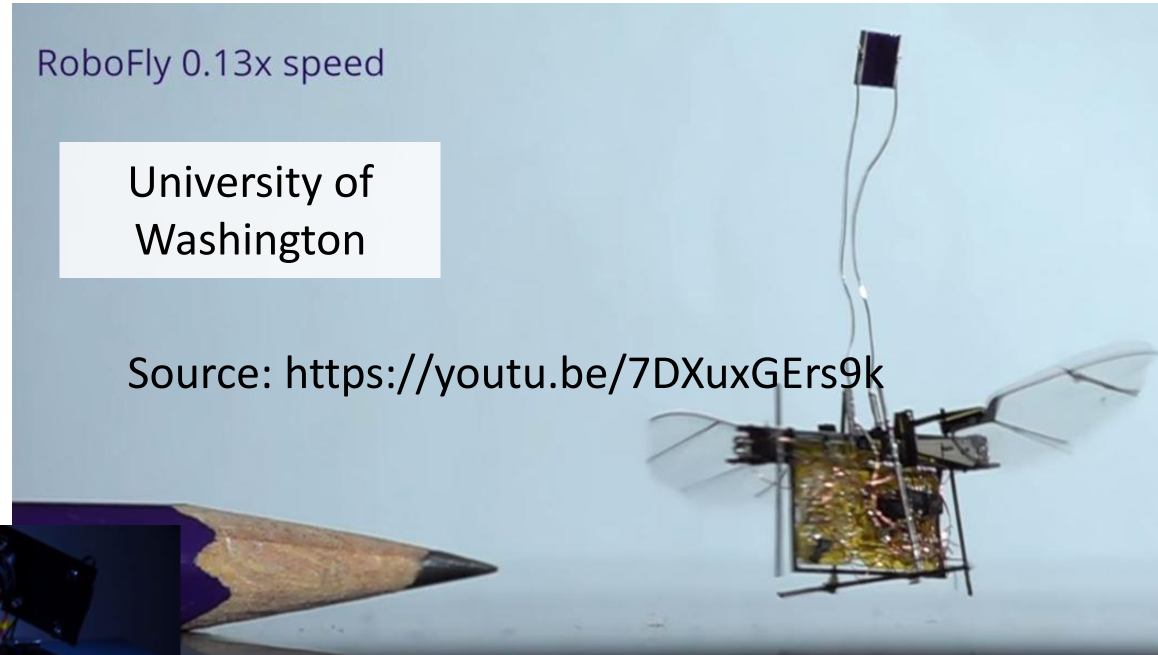


Dickinson and Brown, 54% (1975)



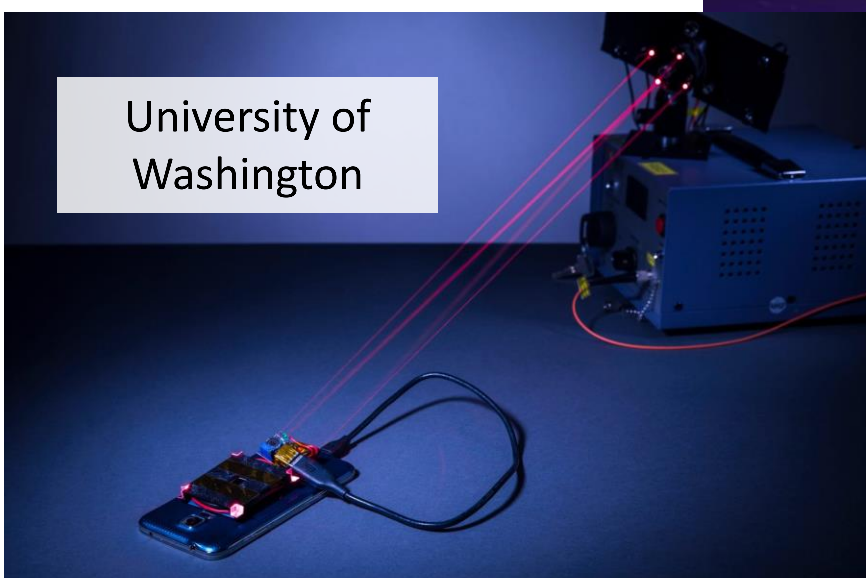
Mitsubishi Electric 5.8 GHz 55m (2015)

Power Beaming University Research



University of Washington

Source: https://youtu.be/7DXuxGErs9k



University of Washington

Source: https://newatlas.com/laser-wireless-charging-system/53492/

Power Beaming Applications

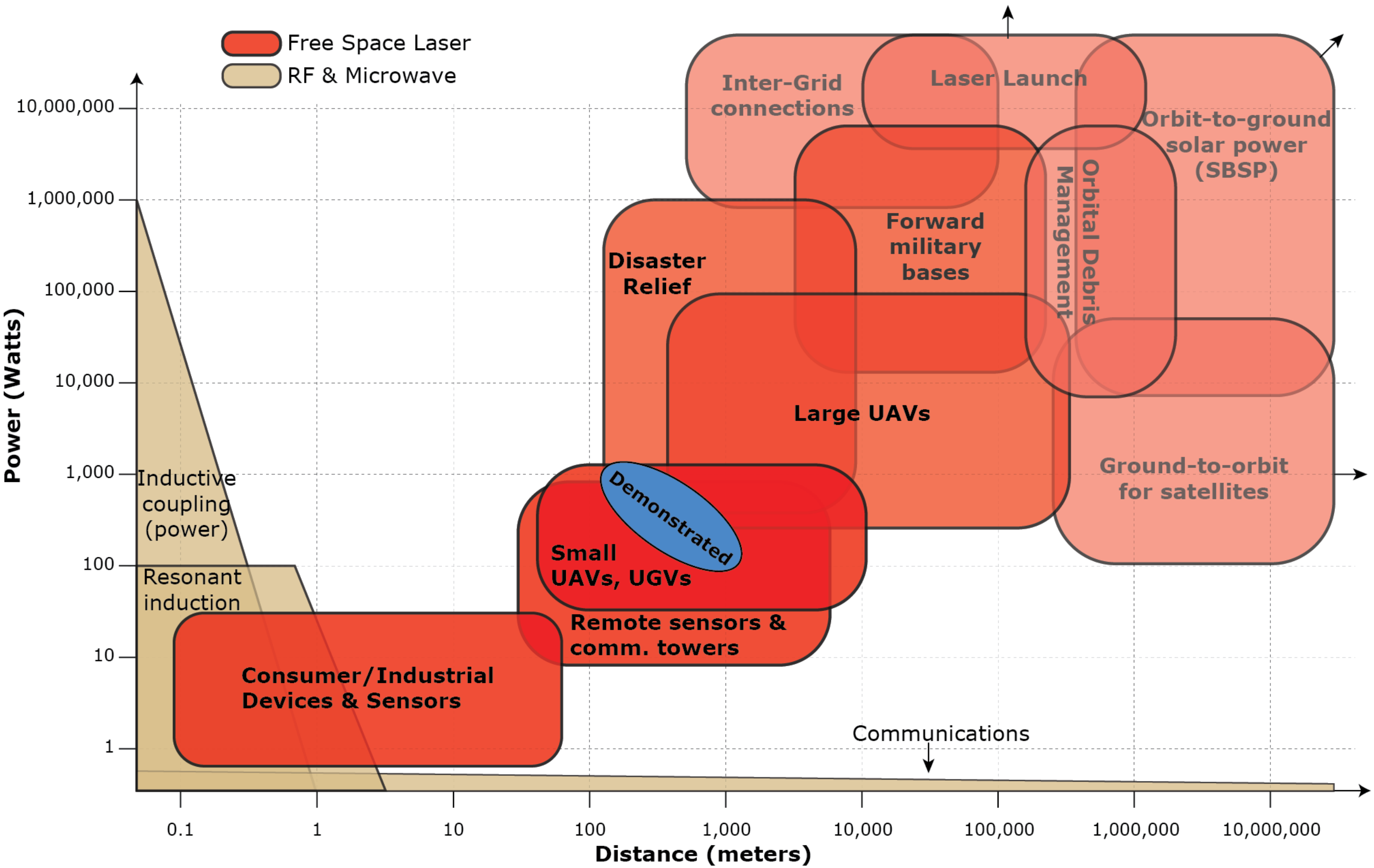


Figure credit: PowerLight (formerly LaserMotive)

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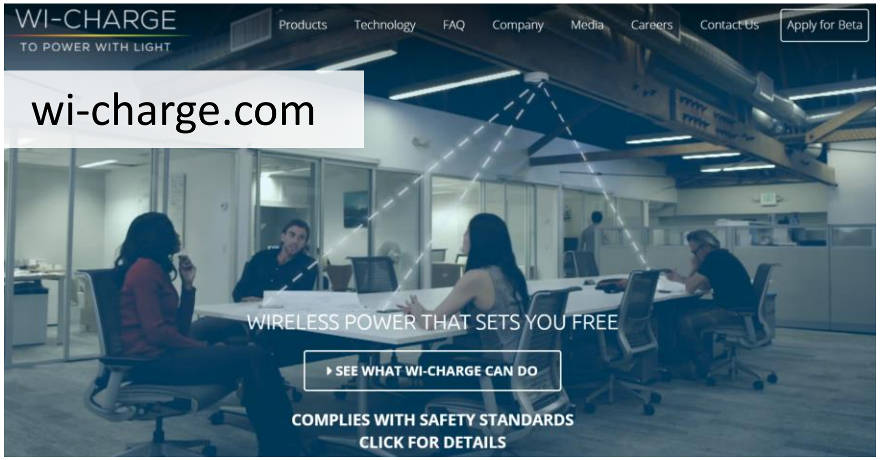
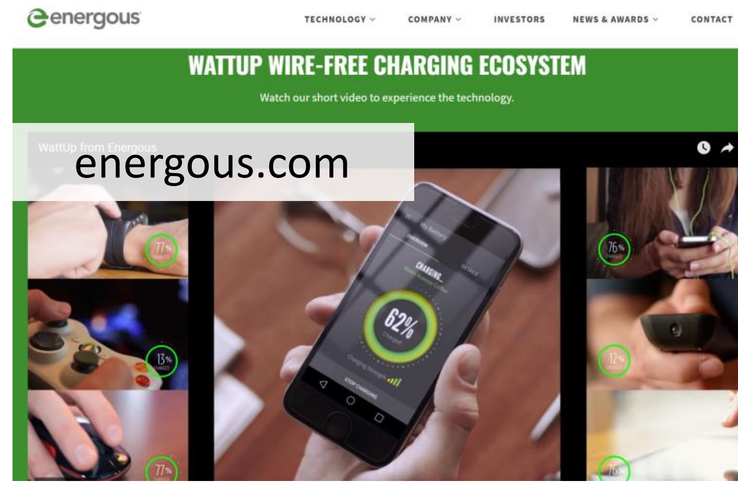
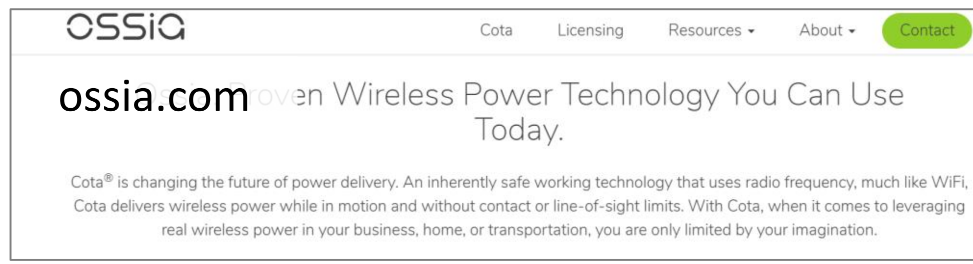
Power Beaming for Consumer Electronics







Generally speaking, companies targeting consumer electronics aim to provide a few watts over a few meters.
Methodologies: radiofrequency, optical, acoustic

Power Beaming for Drones?

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

BY TODD BISHOP on July 23, 2016 at 10:56 am

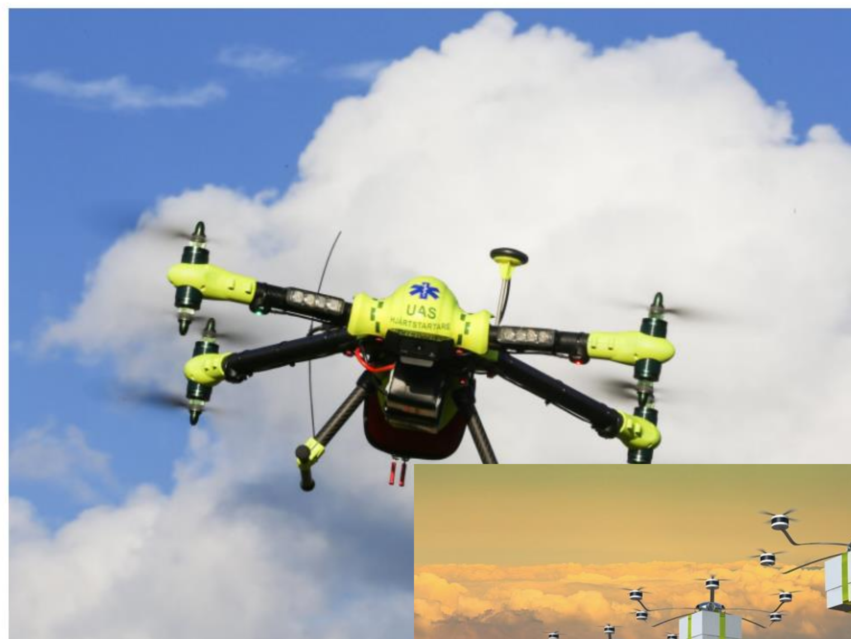
4 Comments | Share | Tweet | Share 179 | Reddit | Email

https://www.geekwire.com/2016/7-eleven-completes-historic-slurpee-delivery-via-drone-beating-amazon-punch/

Could Drones Help Save People In Cardiac Arrest?

June 13, 2017 · 11:34 AM ET

COURTNEY COLUMBUS

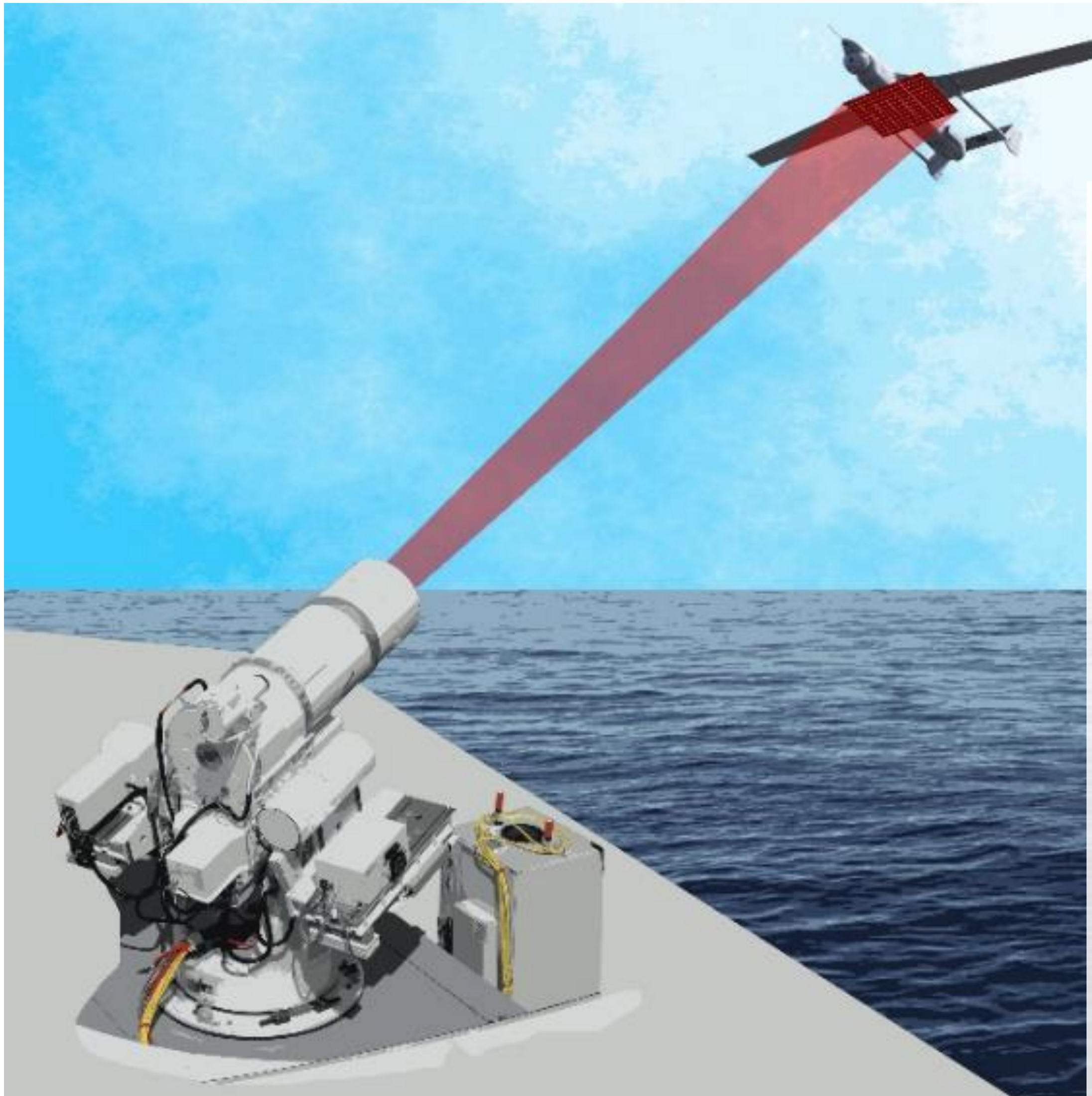


Drones carrying automated external defibrillators got to the sites of p
according to test runs conducted by Swedish researchers.
Andreas Claesson/Courtesy of FlyPulse

http://www.npr.org/sections/health-shots/2017/06/13/532639836/could-drones-help-save-people-in-cardiac-arrest

http://mydronelab

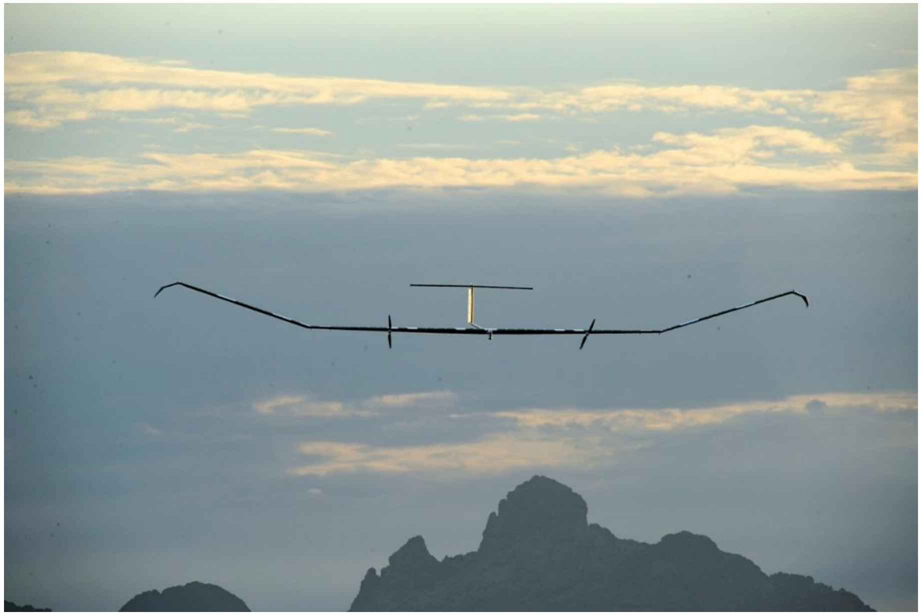
Power Beaming Applications: Autonomous and Remotely Operated Systems



Increased:
- Dwell time
- Payload capacity
- Operational flexibility

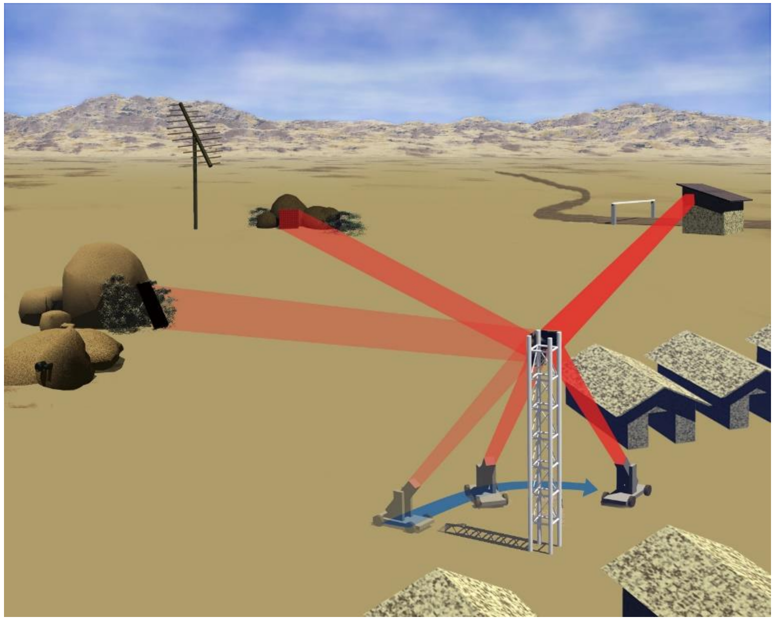
Specific applications:
- Intel, Surveillance, Recon
- Communications
- Off-board countermeasures
- Unattended sensors/buoys
- Logistics, supplies delivery
- Convoy/port protection

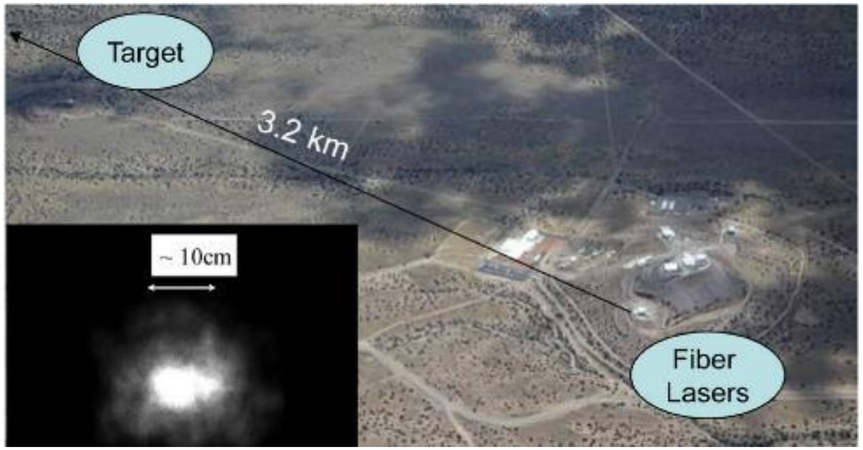
Example Platform: High Altitude, Long Endurance UAV



- 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: Forward Power Distribution Network





Increased:
- Power distribution flexibility
- Resilience

Specific applications:
- Remote site energy resupply
- Ship-to-shore energy provision
- Unattended sensors

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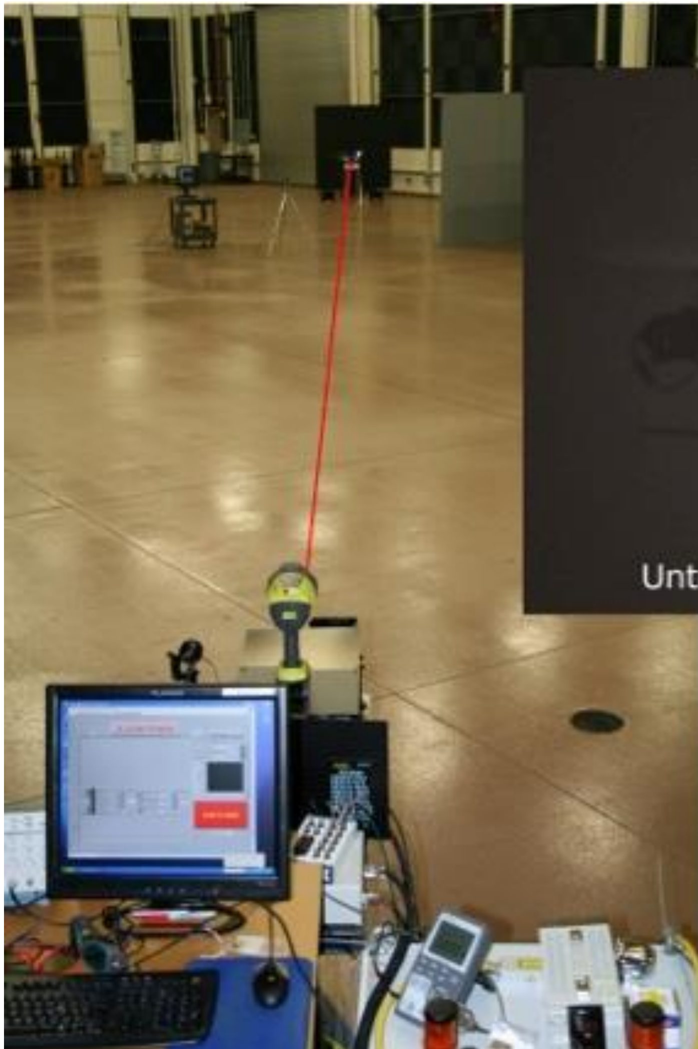
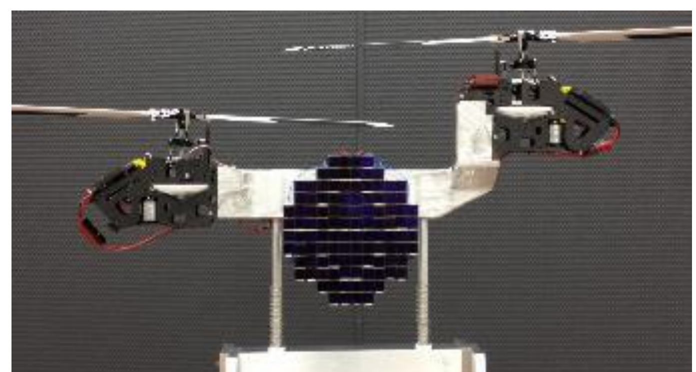
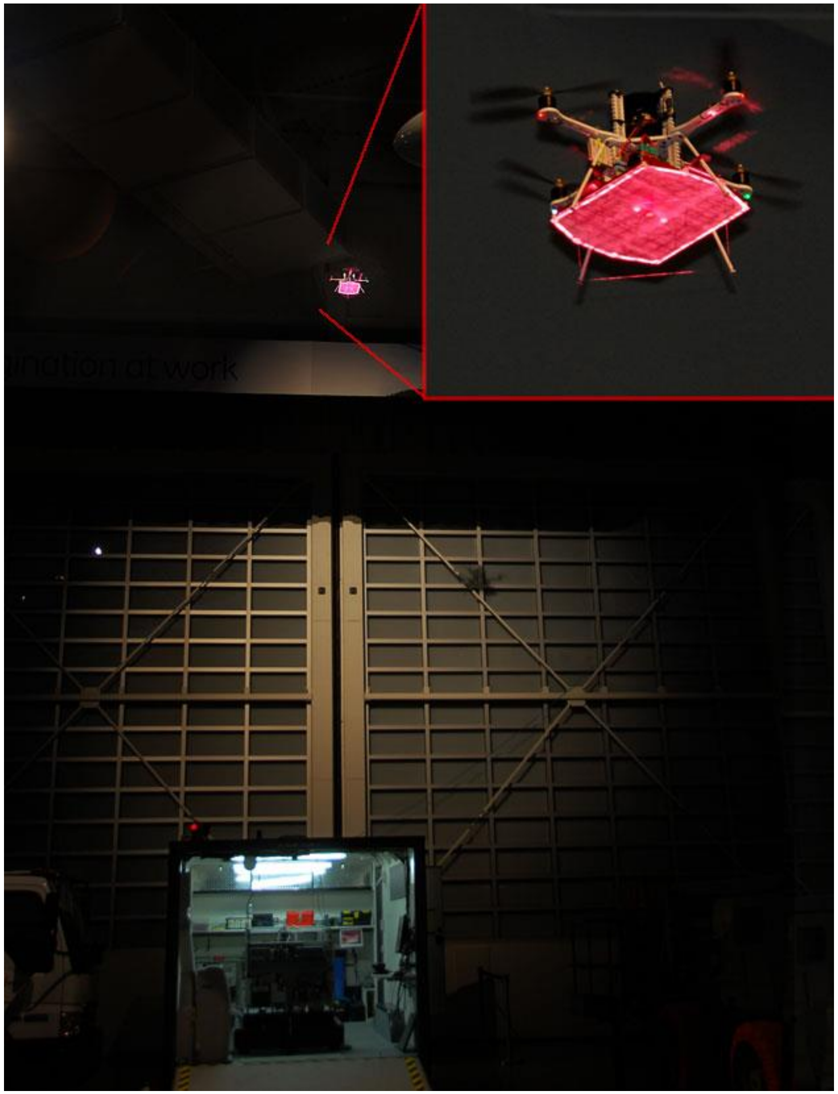
NRL Laser Power Beaming Demonstration



Total weight < 2kg
PV output 160-190 W
Voltage 11 V dc



PowerLight Quadcopter Demo



- Partnered with Ascending Technologies (later bought by Intel)
  - 2 months from 1st meeting to record-setting demo flight
- Specific power 790 W/kg
- Safe (ANSI Z136) reflections on ground
  - Measured with optical power meter
  - Direct beam not accessible
- 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

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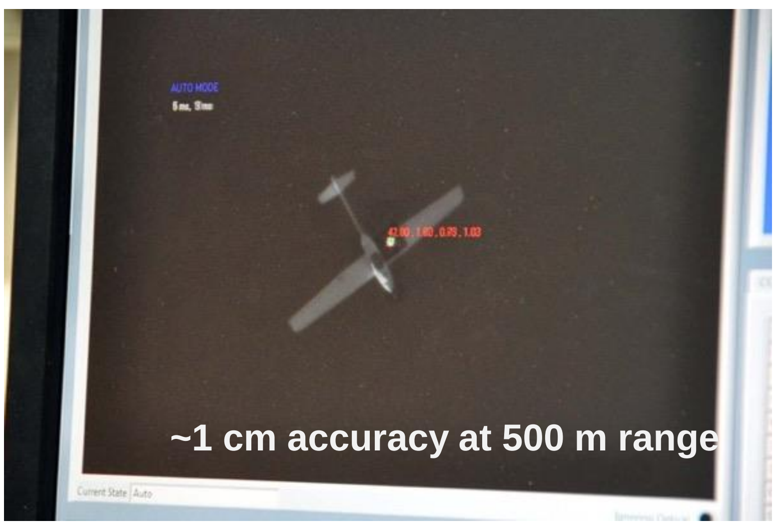
PowerLight Fixed Wing UAV Demo

Proof-of-concept flights in southwest US desert



~1 cm accuracy at 500 m range

- 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 beam center wandered >5 cm off center of PV array
- Automatic beam shut-off when entering Laser Clearinghouse-defined windows
  - 147 segments, total width 46° centered on vertical
- Robust receiver: undamaged even on landings causing airframe damage

Key Concluding 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

Field Regions

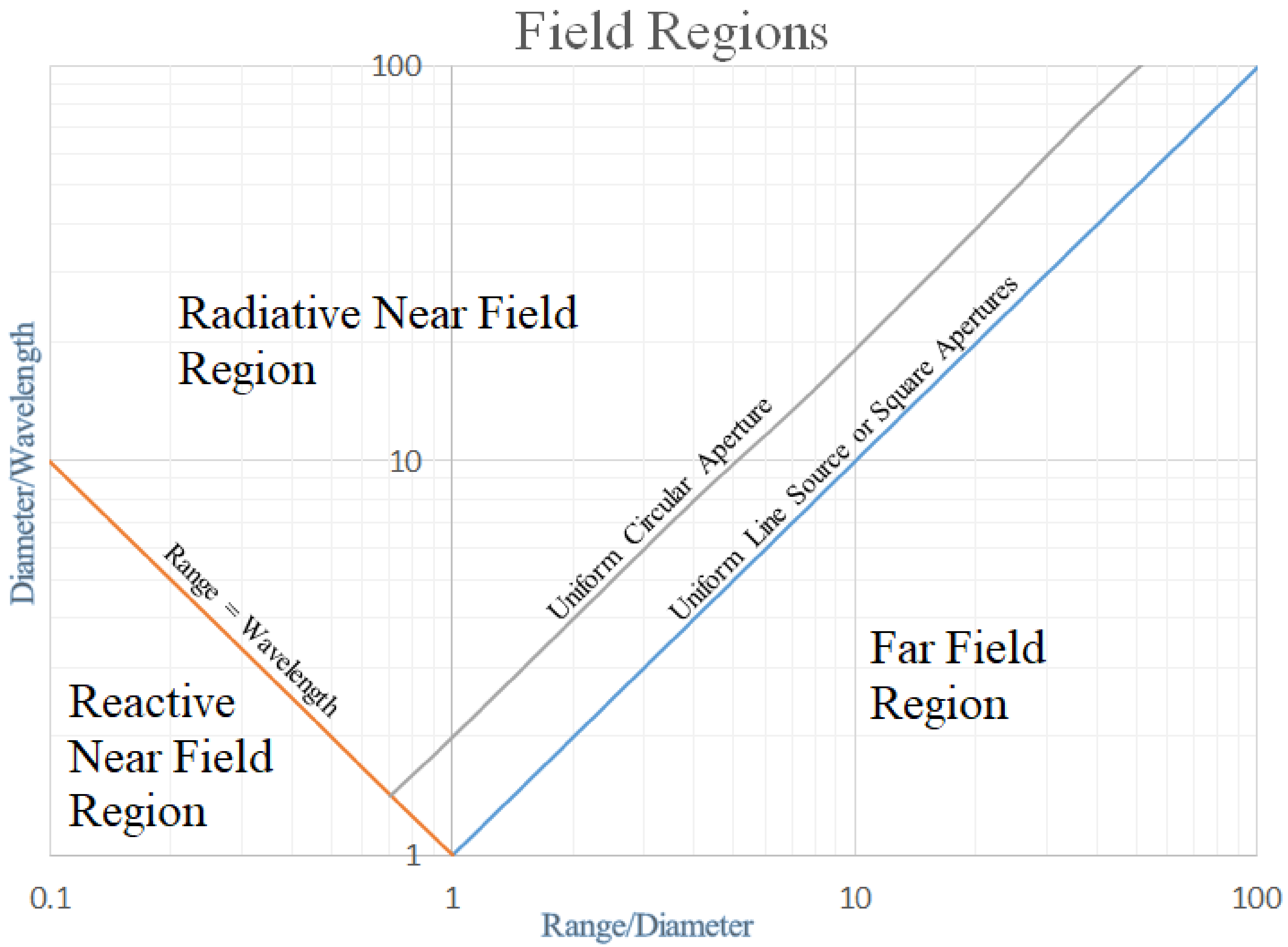
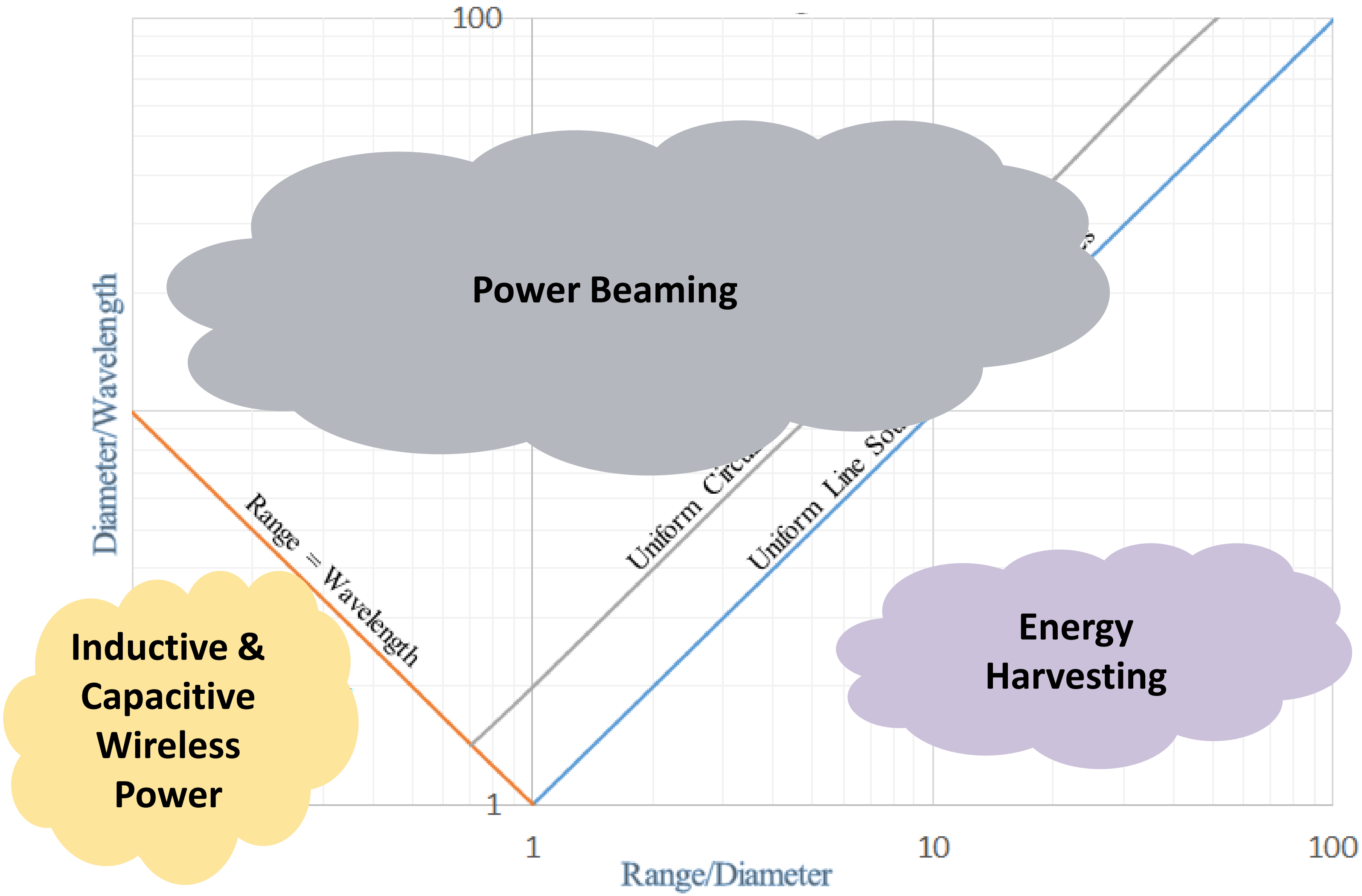


Figure recreated by Kaylin Borders from *Microwave Scanning Antennas* by R. C. Hansen

Field Regions



Attenuation of EM Waves By The Atmosphere

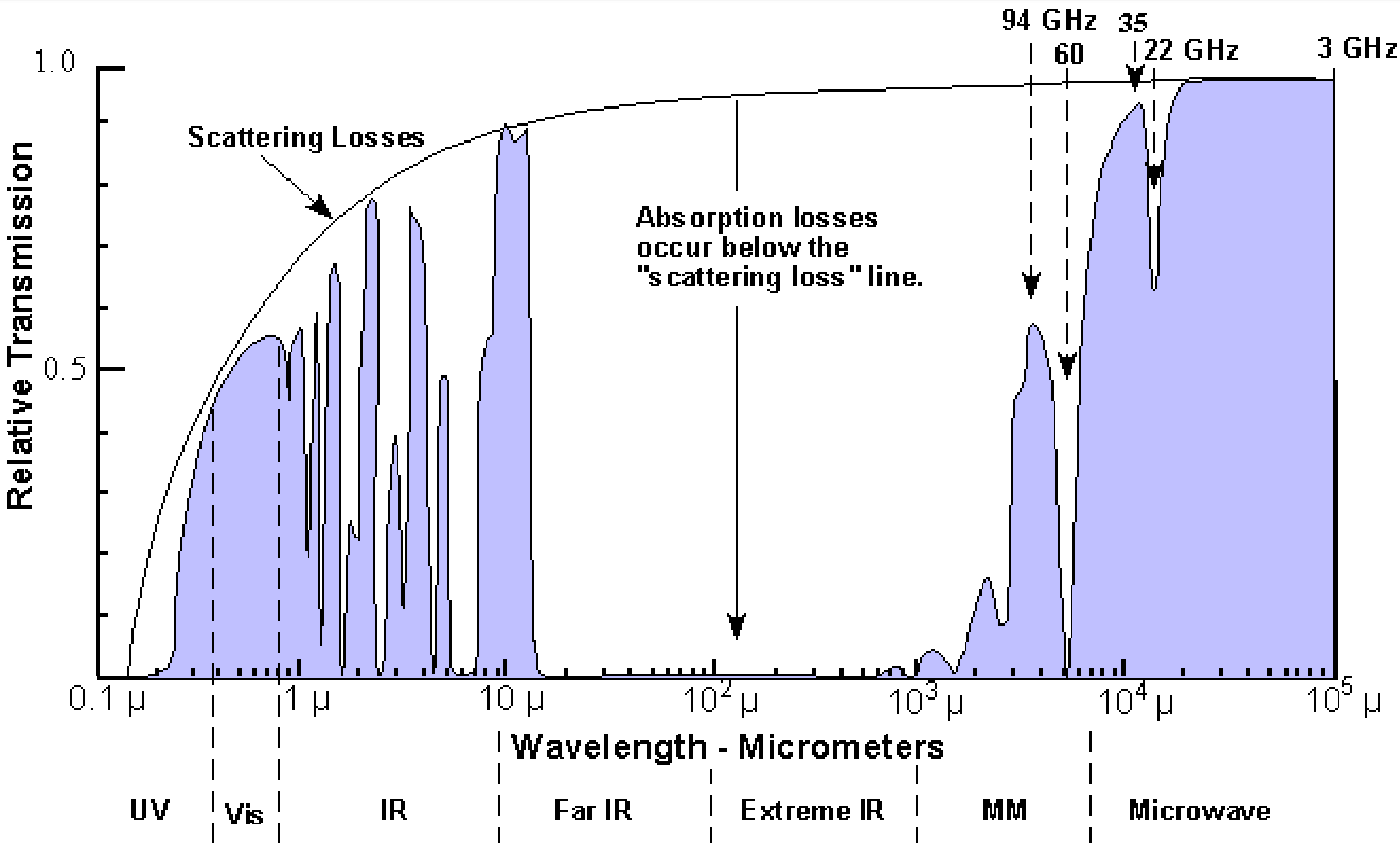


Figure from https://upload.wikimedia.org/wikipedia/commons/7/78/Atmosph%C3%A4rische_Absorption.png

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The Power Beaming Leader Board

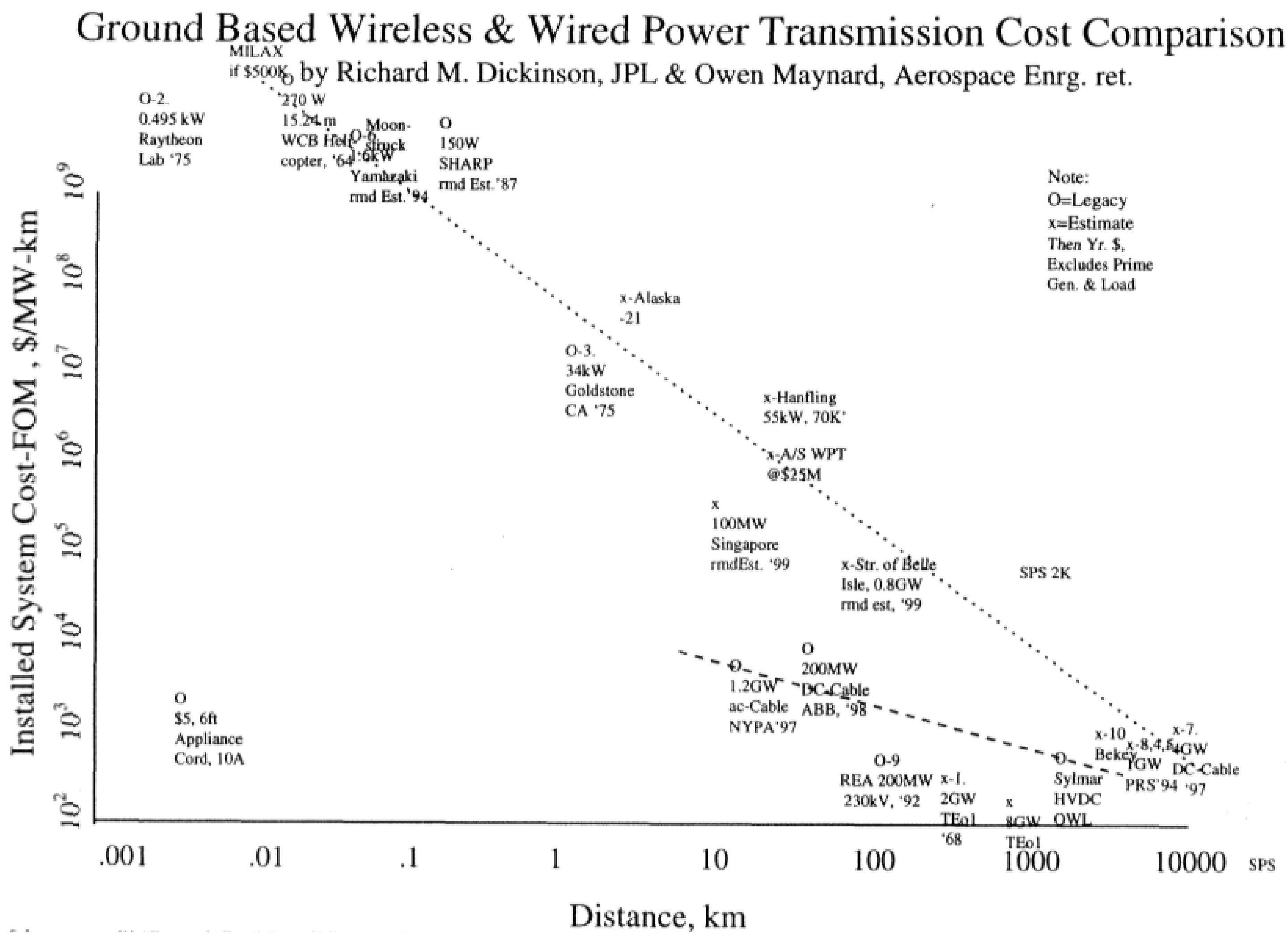
Category	Record	Year	Demonstration
Longest Range	1.55 km	1975	JPL-Raytheon Goldstone
Most Power Delivered	34 kW	1975	JPL-Raytheon Goldstone
Highest Efficiency	54%	1975	Brown & Dickinson

Possible Power Beaming Record Subcategories

- Modality
  - Microwave
  - Laser
- Beam path orientation/location
  - Horizontal in atmosphere
  - Vertical in atmosphere
  - Space
- "Honorable Mentions" that demonstrate a compelling characteristic, but that failed 1-1-1
  - Closed-loop beam control
    - (e.g. Mankins & Kaya 148 km Hawaii demo)
  - Cost factors

Source:
http://www.thespacereview.com/article/1210/1
"A step forward for space solar power" by Jeff Foust, 2008-09-15

Ground Based Wireless & Wired Power Transmission Cost Comparison



Title	Range (m)	Rx output (W)
Lasermotive NASA Challenge Pmax	1,000.0	400.0
SHARP	150.0	150.0
MILAX	8.5	88.0
Brown & Dickinson Lab Demo	1.7	496.0
JPL-Raytheon Goldstone Demo	1,550.0	34,000.0
Moonstruck Rover	61.0	450.0
Outside test – Sichuan University	1,600.0	80.0
Inside test – CAST & Xidian University	11.0	8.0
Kawashima helicopter	51.0	40.0
NRL UAV	40.0	190.0
HI Discovery Channel	148,000.0	0.2
55 m point to point experiment	55.0	325.0
Cota Ossia	5.0	0.5
Wi Charge	5.0	5.0
High-Power High-Efficiency Laser Power Transmis	100.0	9.7
Lasermotive NASA Challenge Dmax	400.0	1,000.0
Univ. of Maryland "Bang Goes the Theory"	240.0	1.5
Straits of Belle Isle WPT link	25,000.0	110,000,000.0
SPS 2000	1,100,000.0	10,000,000.0
SPS-ALPHA 2 GW	35,786,000.0	2,080,000,000.0
1-sun MEO CASSIOPeiA	24,000,000.0	688,000,000.0

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