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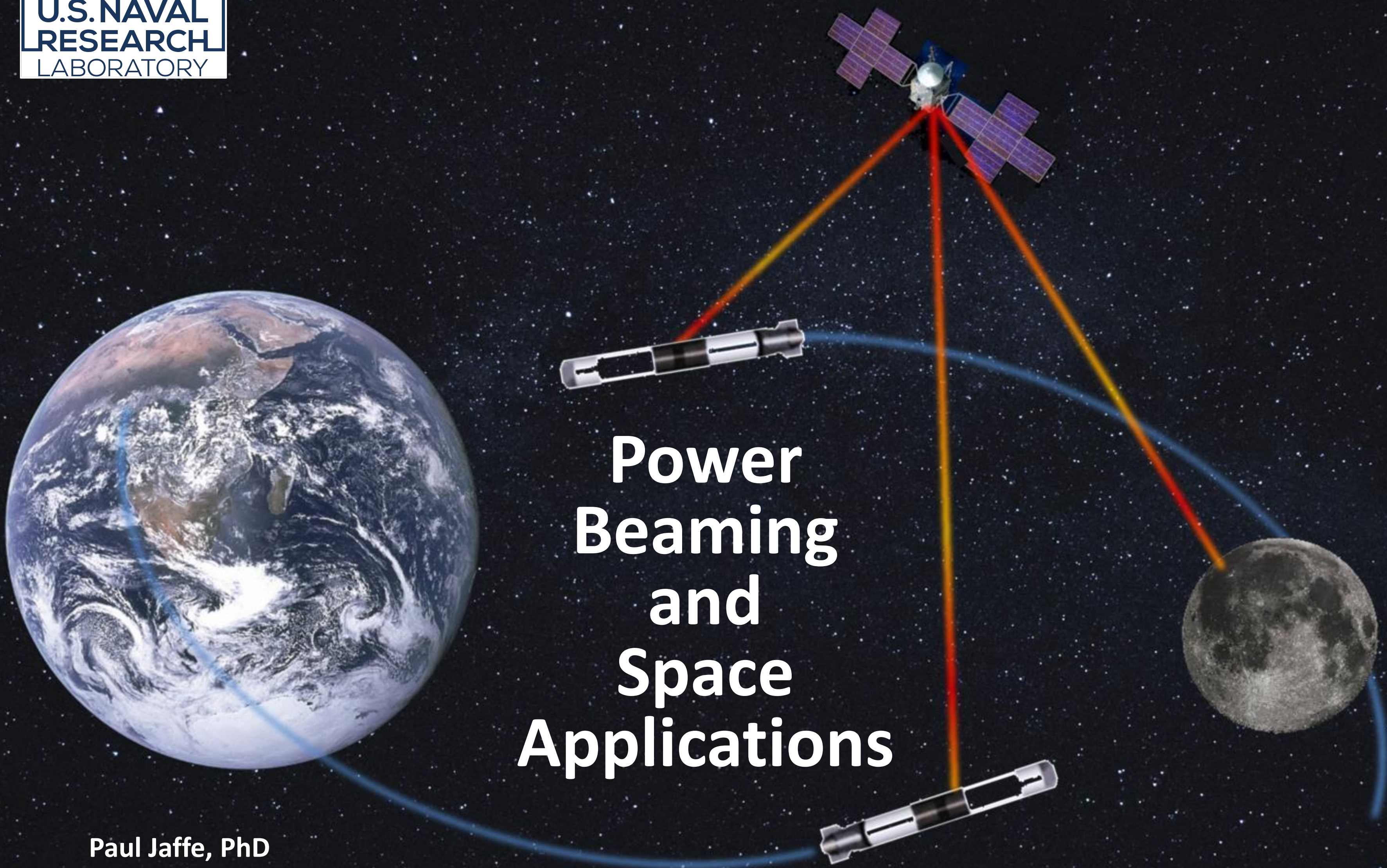
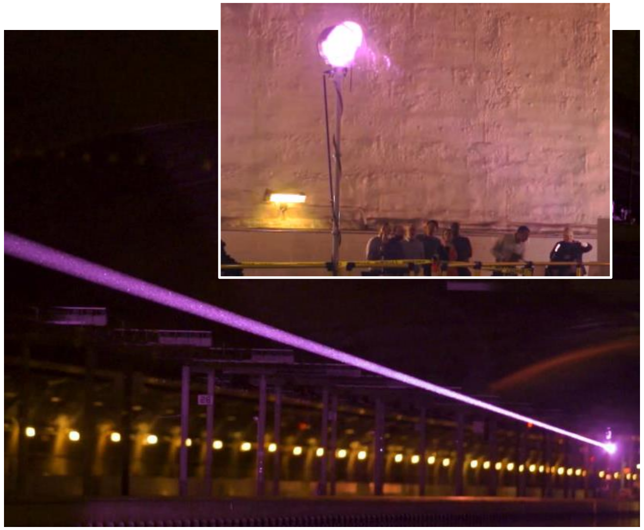
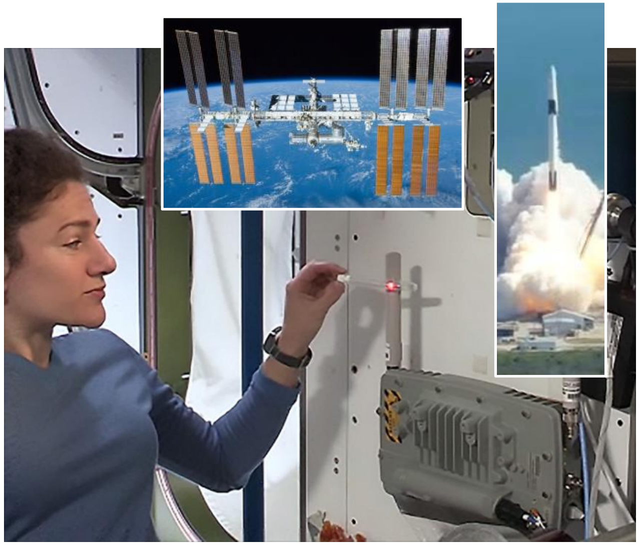


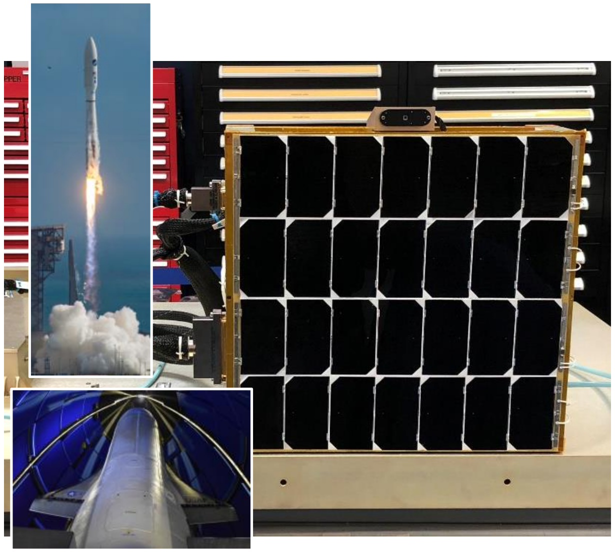
Power Beaming and Space Applications

Paul Jaffe, PhD
Paul.Jaffe@nrl.navy.mil

Recent Power Beaming and Space Solar Activities at the U.S. Naval Research Laboratory







https://youtu.be/Xb9THqrXd4I

In 2019, a power beaming demonstration in Bethesda, MD showed the feasibility of safe optical power beaming. >400W was sent safely over a distance of 325 m

https://youtu.be/zo7w0D6vz5g

In 2020, the LEctenna wireless power STEM demonstration using Wi-Fi on the International Space Station was conducted by Astronaut Jessica Meir

https://youtu.be/NTrGFDQPHV8

In 2020, a flight experiment for sunlight-to-microwave conversion for space solar was successfully launched on the X-37B Orbital Test Vehicle and operated

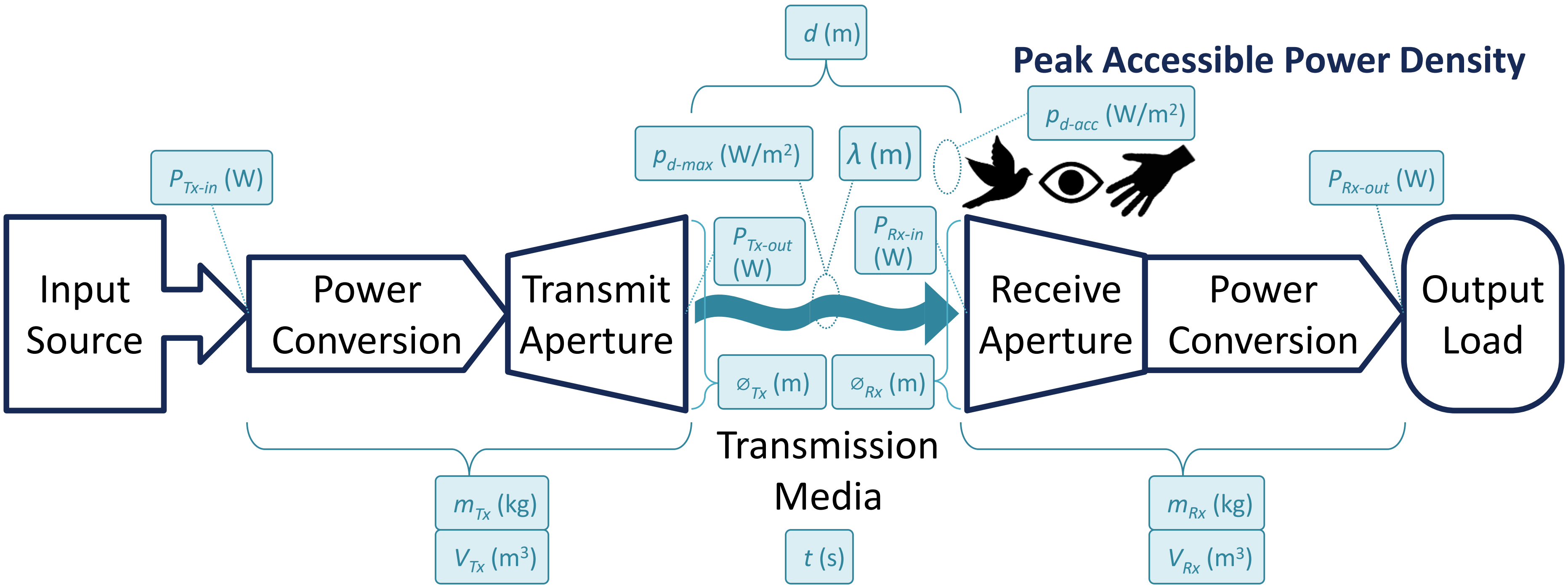
What is Power Beaming?

Power Beaming is delivering meaningful amounts of energy across long spans of free space without moving mass

Easier place to get energy → Power beaming → Harder place to get energy

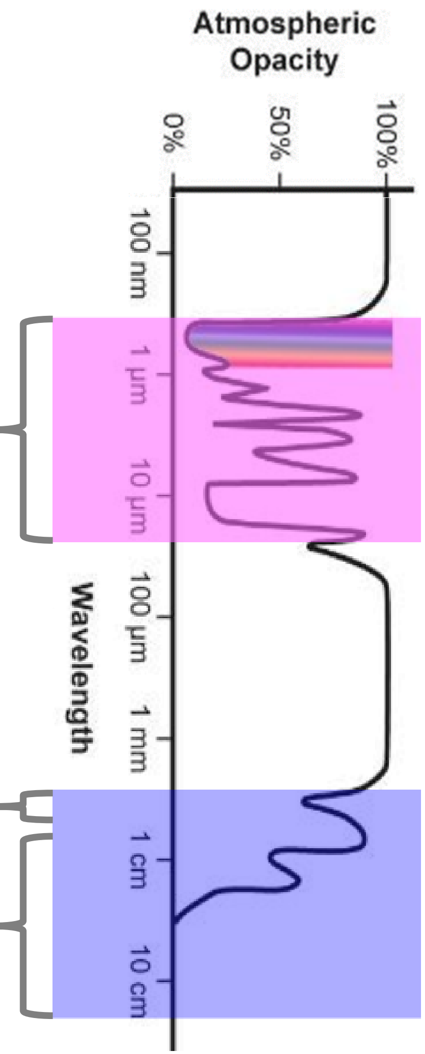
Separation ill-suited for a physical connection

Critical Power Beaming Measurements



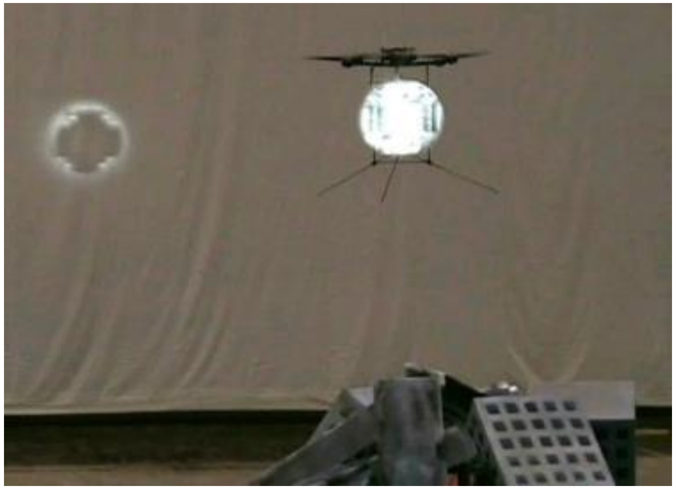
Power Beaming Modalities

- 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



Selected Laser Power Beaming Demos

EADS Astrium tracking laser to power rover (2003)



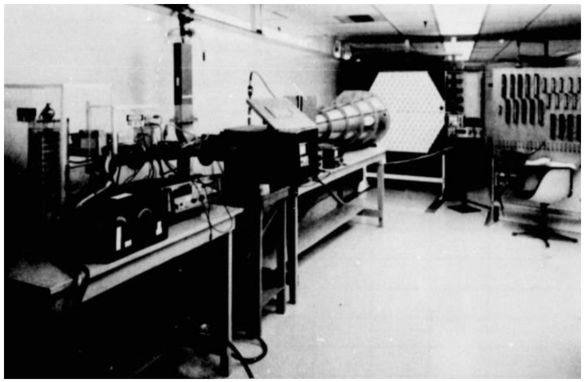
Kinki Univ. & Hamamatsu Photonics Inc. laser power to small helicopter (2007)

Lighthouse DEV Eye-safe laser demo (2012)

LaserMotive outdoor laser power to UAV (2012)

PowerLight point-to-point power link (2019)

Selected Microwave Power Beaming Demos



Dickinson and Brown, 54% (1975)

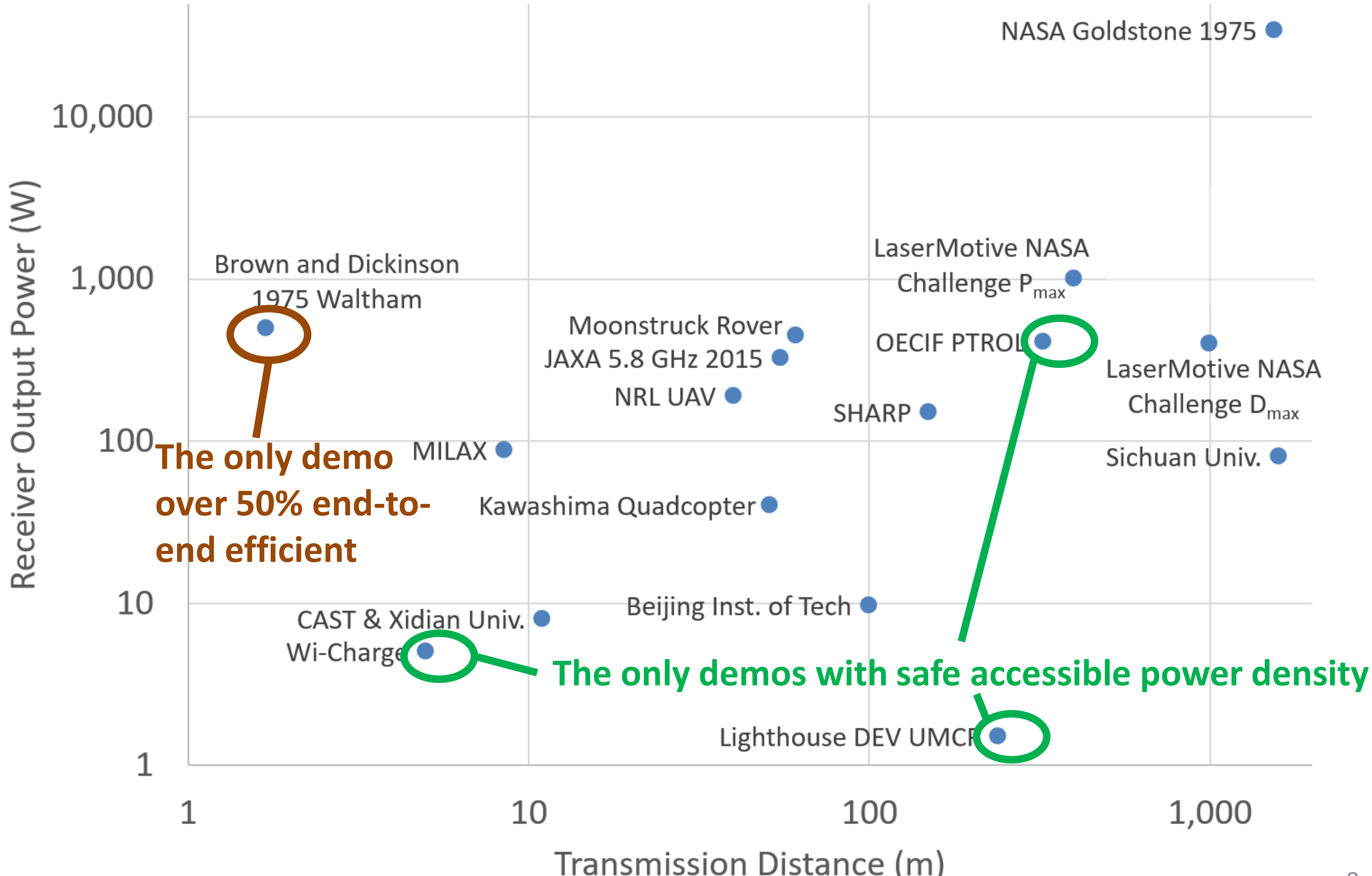
JPL-Raytheon Goldstone, 34 kW, 1.6 km (1975)

MILAX Kobe University (1992)

Aerostat phone charging Kyoto U. (2009)

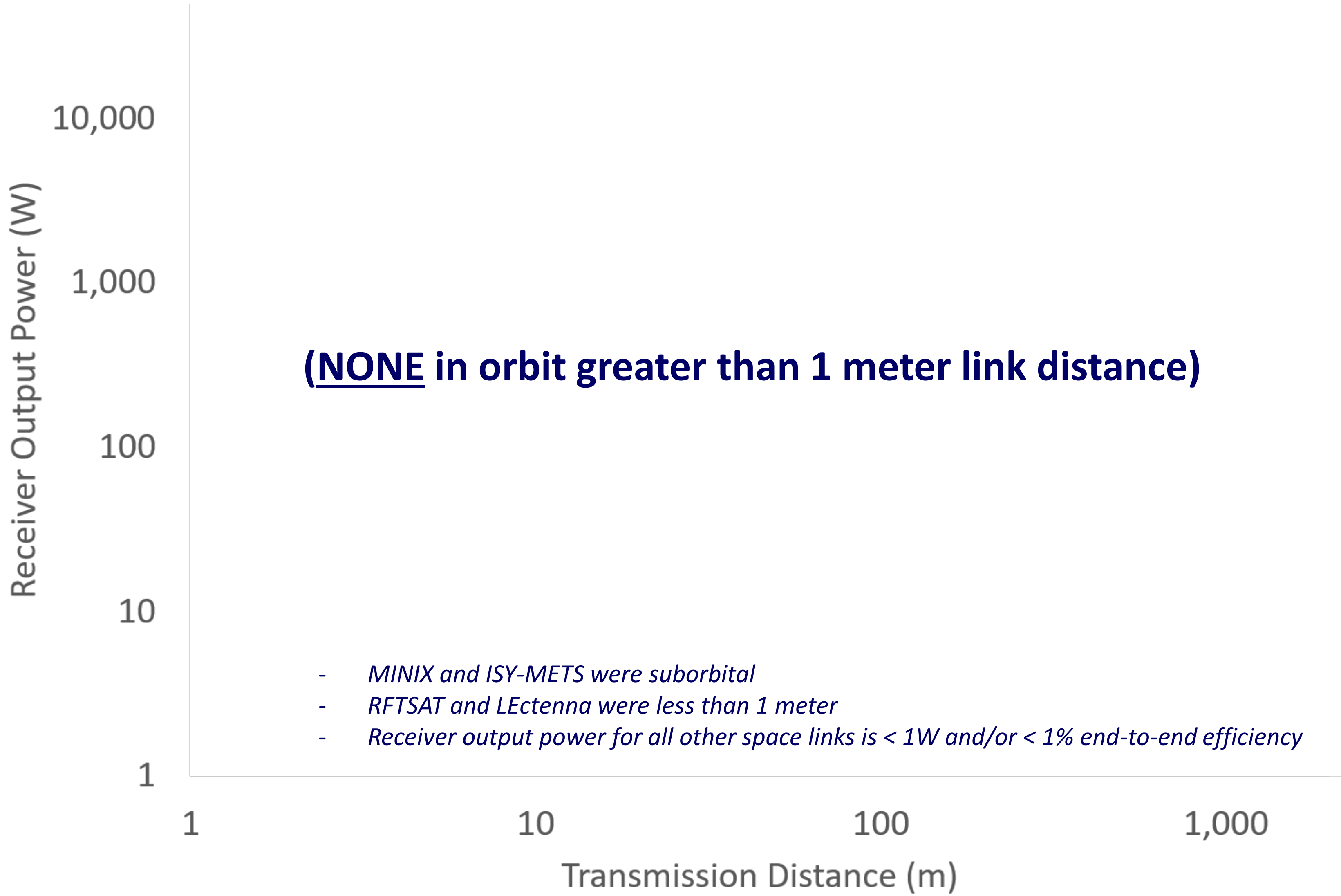
Mitsubishi Electric 5.8 GHz 55m (2015)

Receiver Output Power vs. Transmission Distance for Terrestrial Power Beaming Demonstrations

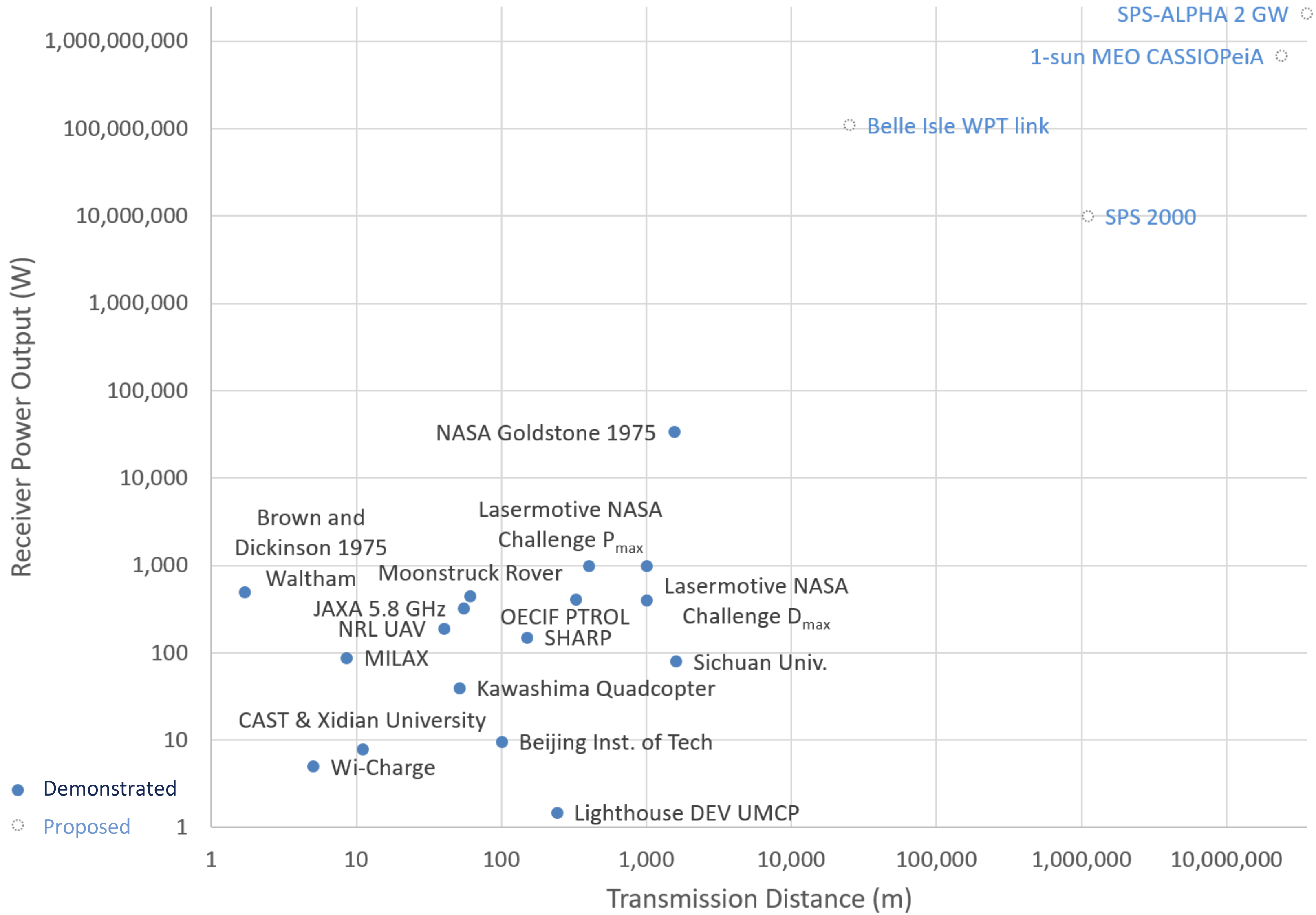


For refs see: C. T. Rodenbeck et al., "Microwave and Millimeter Wave Power Beaming," IEEE Journal of Microwaves, vol. 1, no. 1, pp. 229–259, winter 2021, doi: 10.1109/JMW.2020.3033992.

Receiver Output Power vs. Transmission Distance for Space Power Beaming Demonstrations



Receiver Output Power vs. Transmission Distance



Categorizing Space Power Beaming Links by Link Distance

Link Distance	Link Distance Range	Example Application
“short”	$d \leq 0.01$ km	Inter- or intra- satellite power links
“medium”	$d \leq 100$ km	Lunar power beaming networks
“long”	$d \leq 100{,}000$ km	Solar power satellites
“very long”	$d > 100{,}000$ km	Beamed energy propulsion

Each distance category doesn’t include shorter distances that are covered by another category

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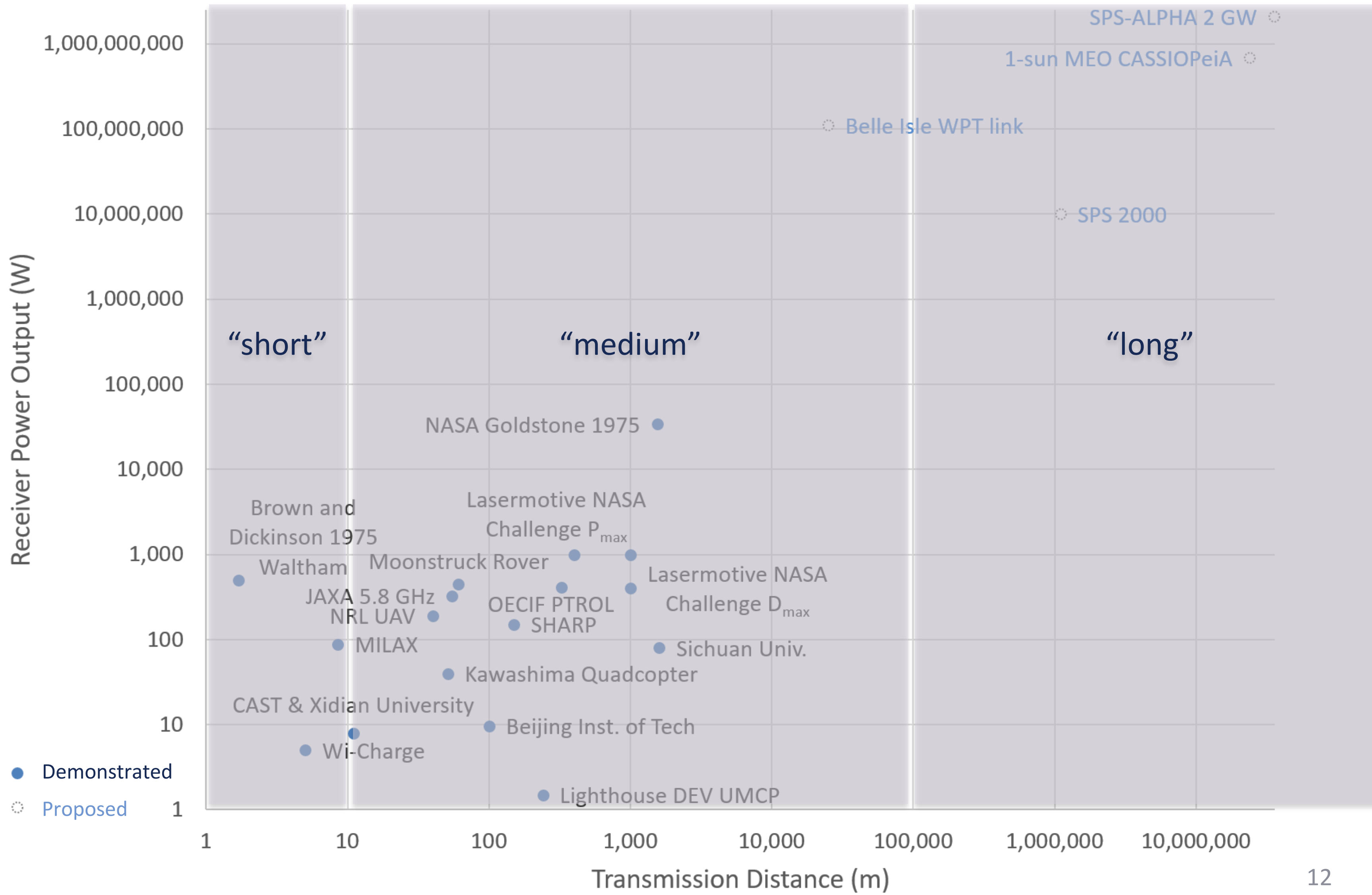
Receiver Output Power vs. Transmission Distance



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"Short" Space Power Beaming Application: Intersatellite Power Links

Intersatellite power links could be used with "fractionated" spacecraft, as was proposed for the DARPA System F6 (Future, Fast, Flexible, Fractionated, Free-Flying Spacecraft United by Information Exchange)

Image credit: DARPA

Reference: https://web.archive.org/web/20111022223133/http://www.darpa.mil/Our_Work/TTO/Programs/System_F6.aspx

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"Medium" Space Power Beaming Application: Planetary Body Power Distribution Network

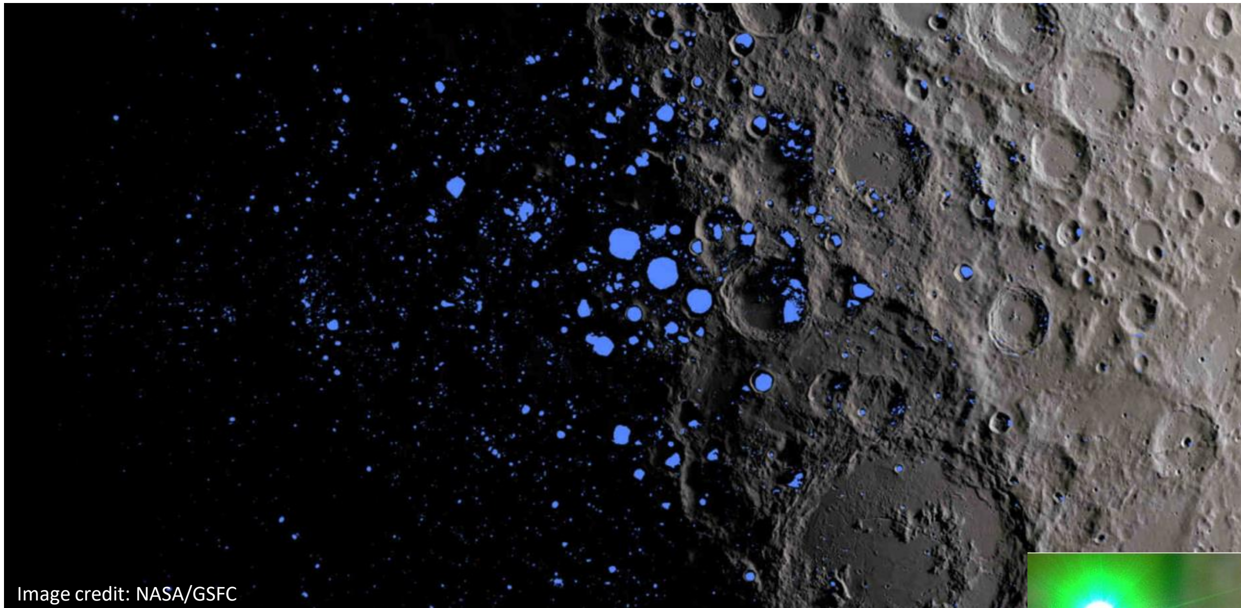


Image credit: NASA/GSFC

Blue regions are permanently shadowed

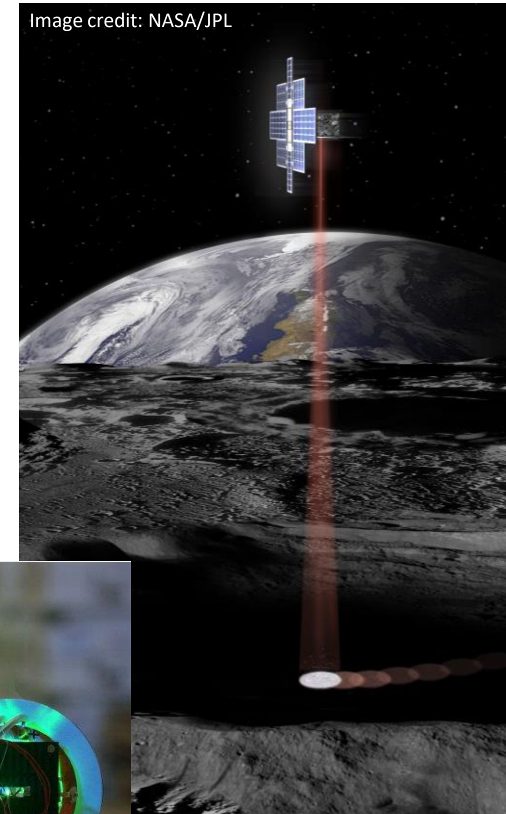


Image credit: NASA/JPL

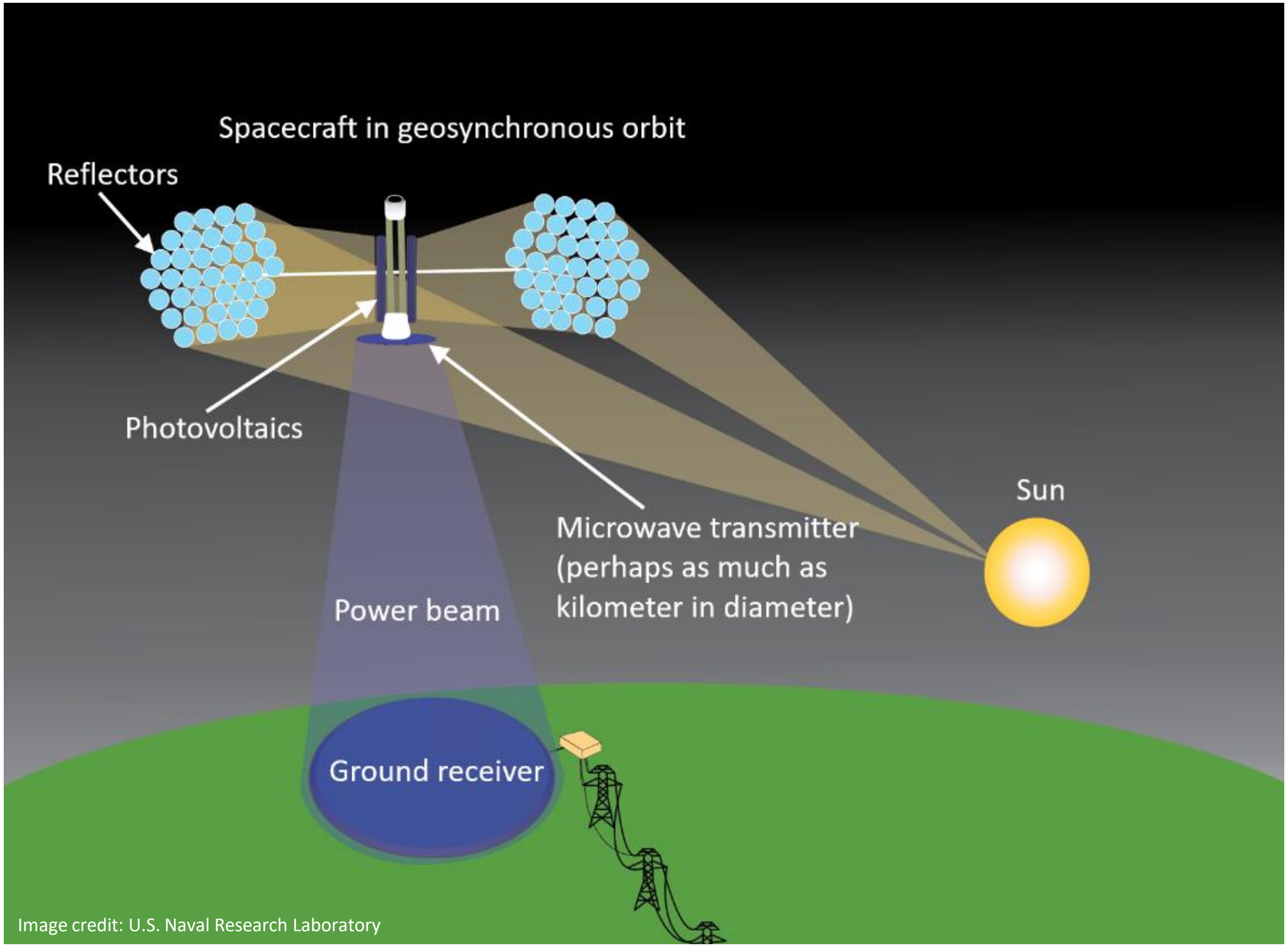
Increases:
- Power distribution flexibility
- Resilience

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


Image credit: Leopold Summerer

“Long” Space Power Beaming Application: Solar Power Satellites (“Space Solar”)

Space Solar is the collection of solar energy in space and its wireless transmission for use on Earth or other bodies

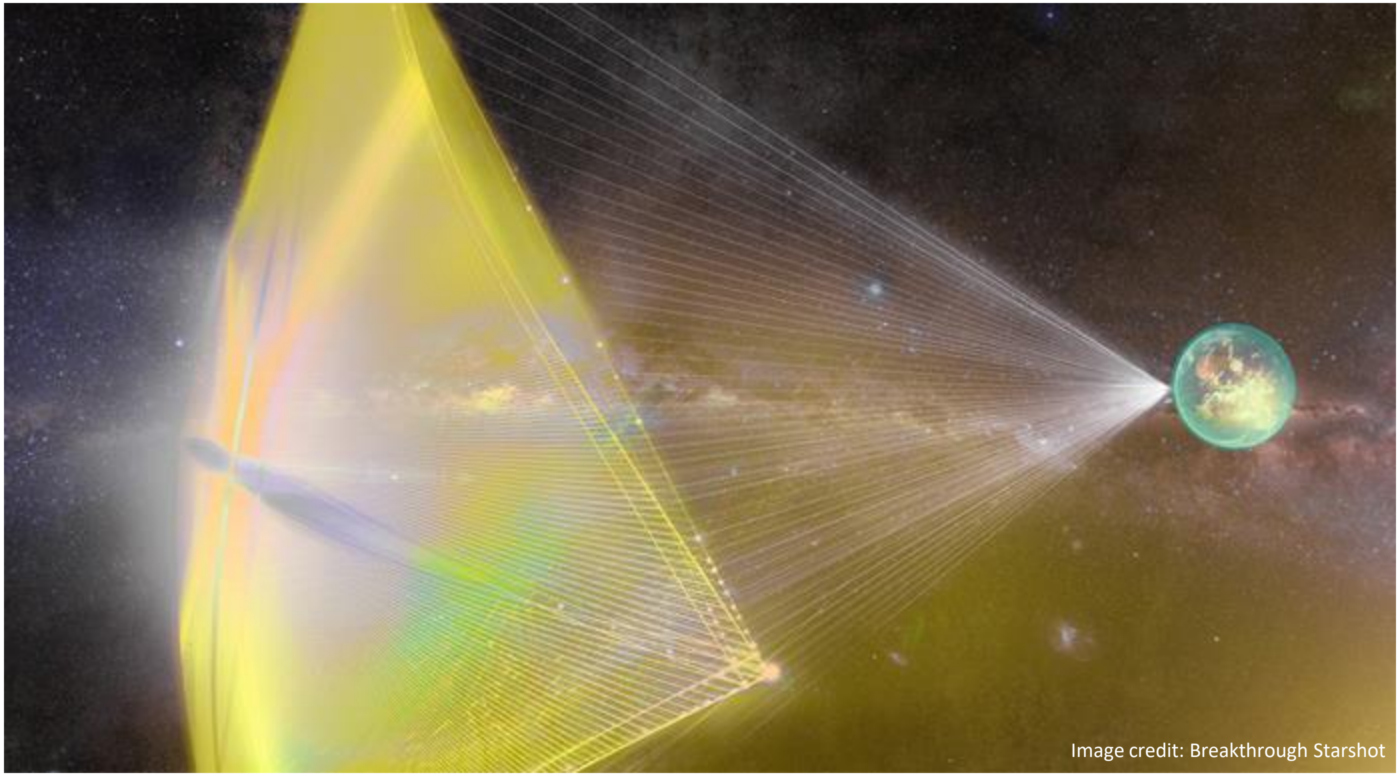


(This depiction is merely one of many proposed implementations)

Reference: https://apps.dtic.mil/sti/pdfs/AD1082903.pdf

“Very Long” Space Power Beaming Application: Beamed Energy Propulsion

Beamed Energy Propulsion could be used to send a spacecraft into interstellar space, as is proposed as part of the Breakthrough Starshot initiative



Reference: https://breakthroughinitiatives.org/initiative/3

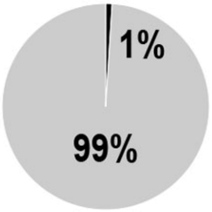
What Next?

- So far, there has not been a power beaming demonstration in orbit spanning > 1 meter with > 1% end-to-end efficiency
- Creating a power beaming link that exceeds these modest thresholds is a logical next step
- What might it look like?

Space Wireless Energy Laser Link (SWELL) Proposed Experiment

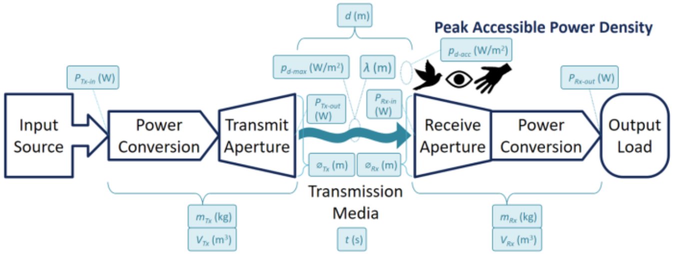
- Establish an optical power beaming link that:
  - Spans > 1 m

  - Operates with > 1% end-to-end efficiency



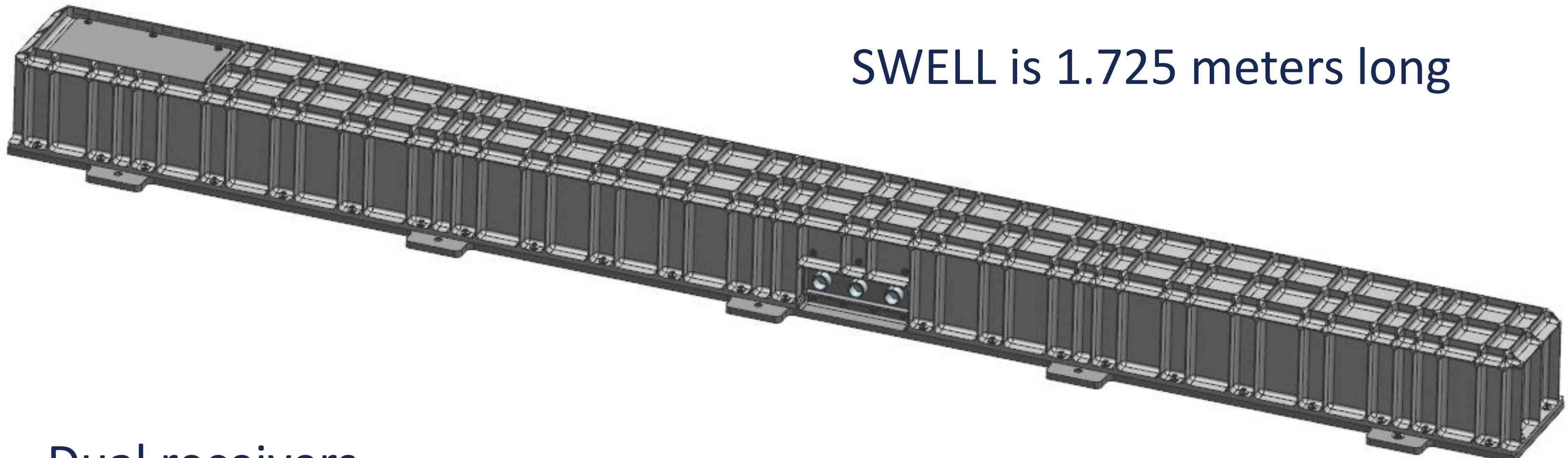
- Operate the link on orbit for > 6 months to characterize system performance and degradation in space

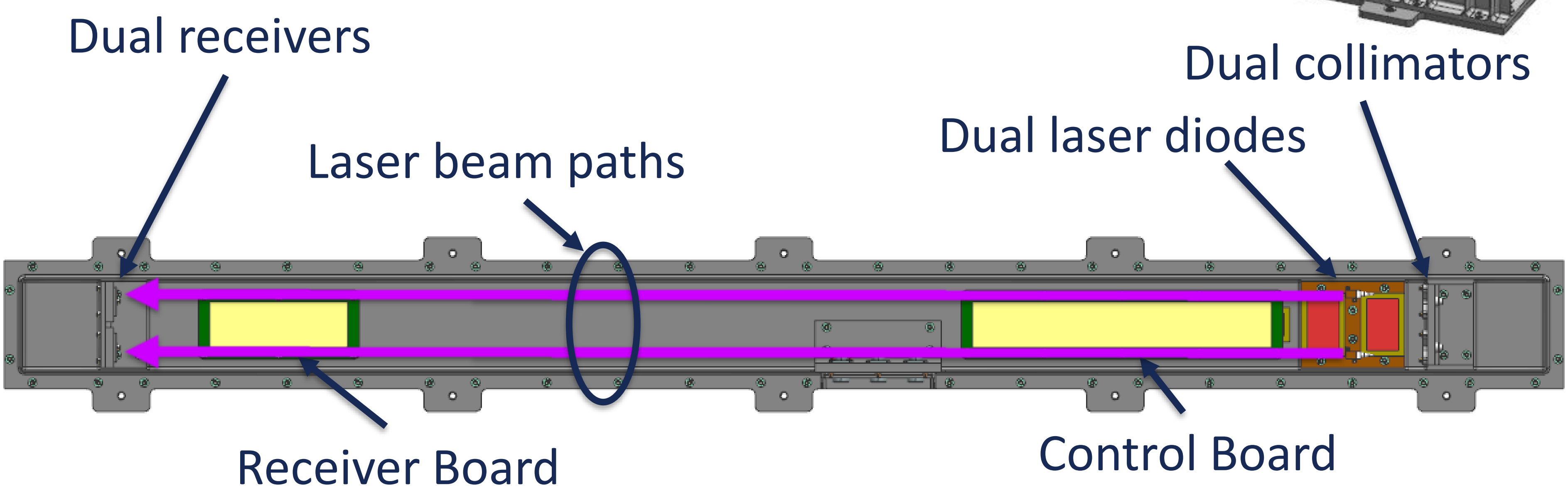
- Measure link performance at maximum efficiency and delivered power to identify key improvement areas



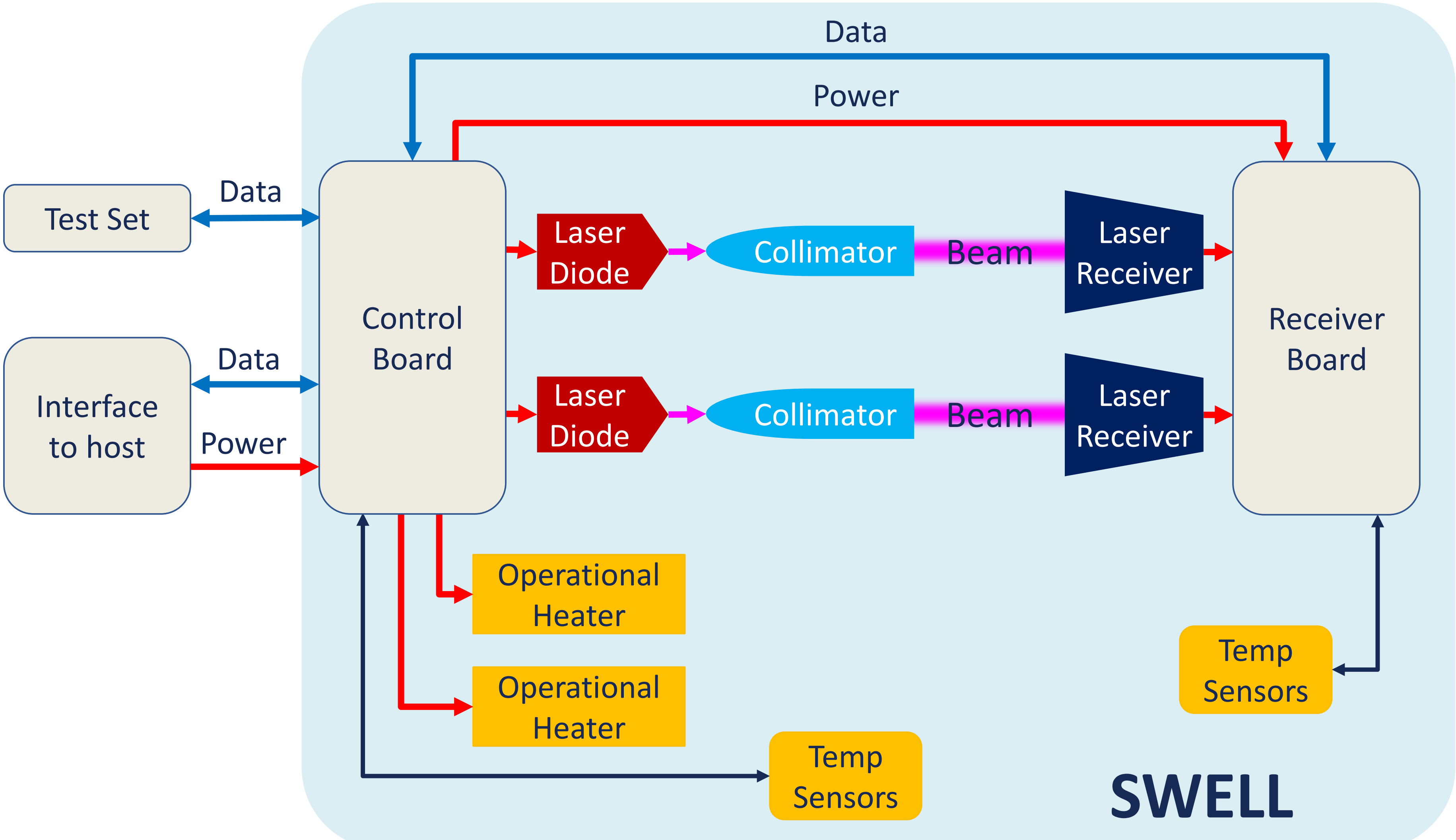
SWELL Mechanical Overview

SWELL is 1.725 meters long





SWELL Functional Overview



Closing Thoughts

- Power beaming offers a range of benefits for space applications
- Power beaming links in space could address a wide range of distances
- To date, there has not been a meaningful demonstration of power beaming in space

The first step towards realizing the potential benefits of power beaming in space is to demonstrate a small-scale link

Thank You for Your Attention

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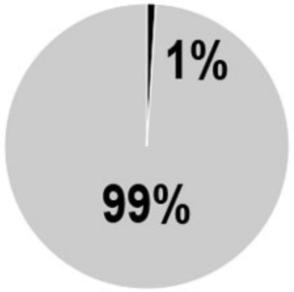
Backup

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**

1-1-1

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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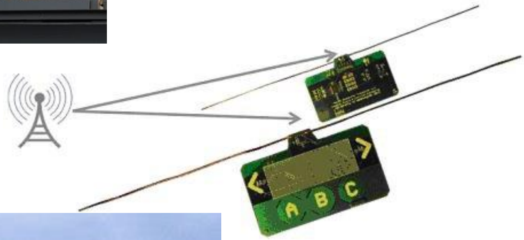
Things That are NOT Power Beaming

- 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

Field Regions

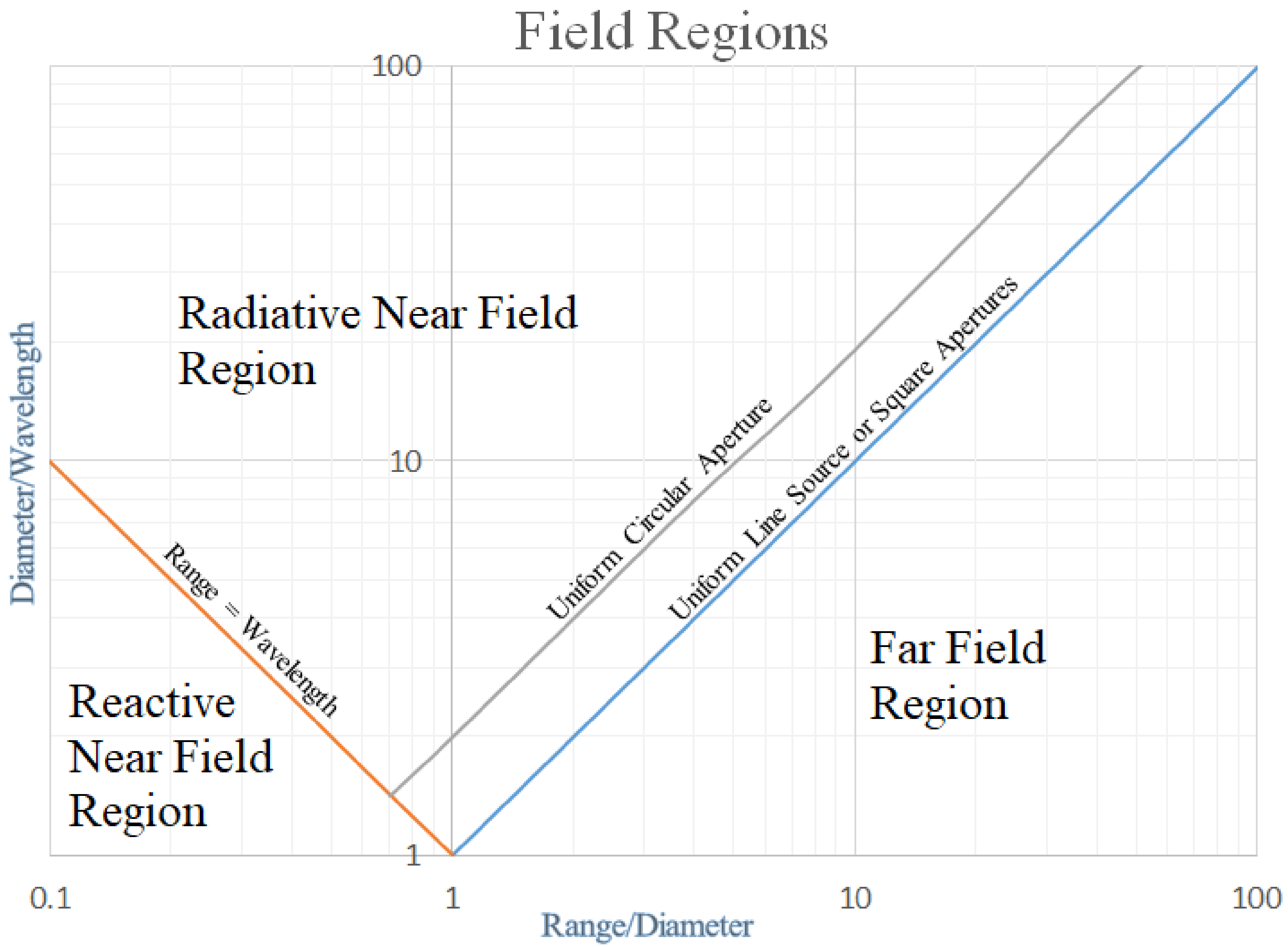
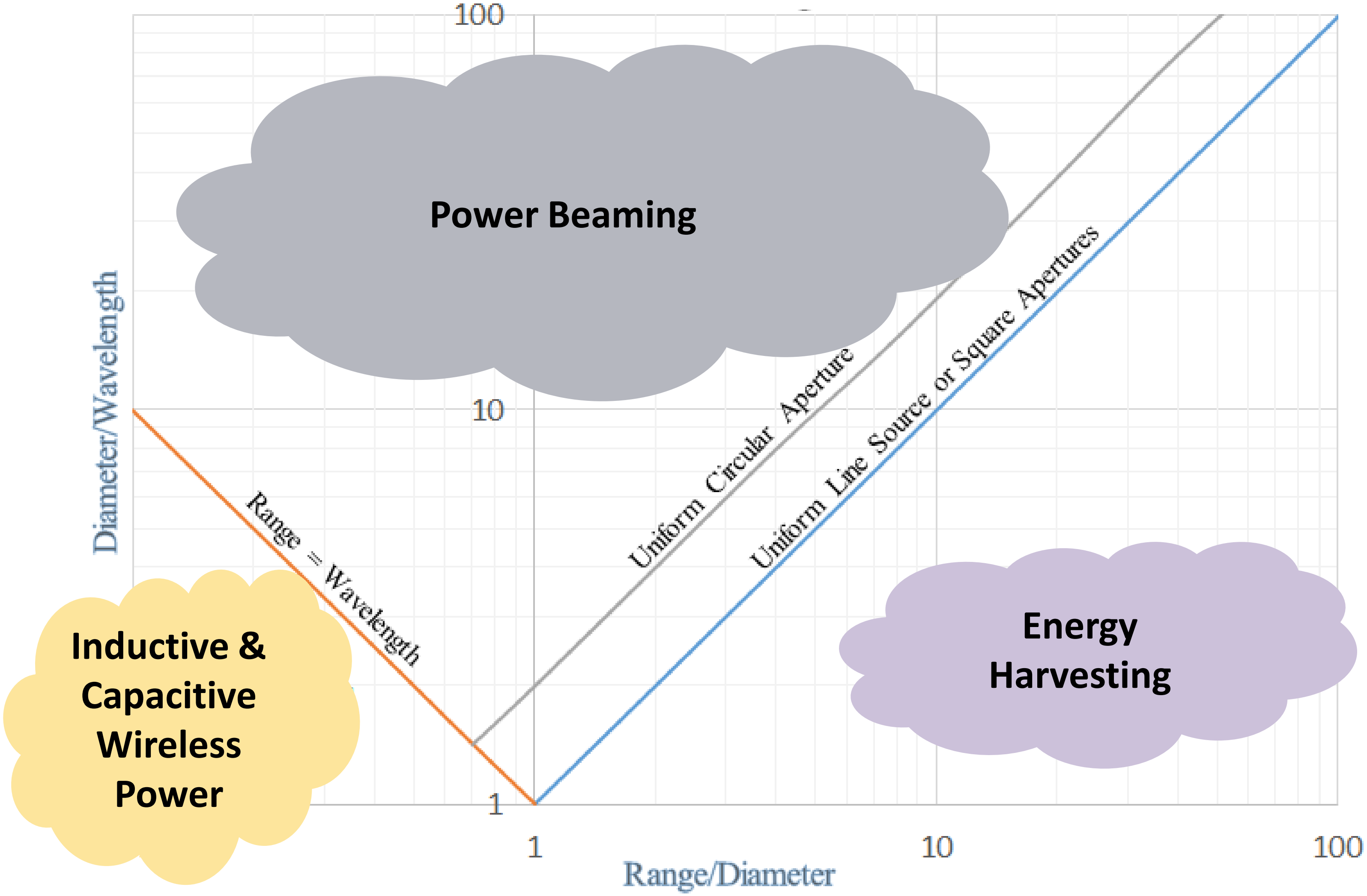


Figure recreated by Kaylin Borders from *Microwave Scanning Antennas* by R. C. Hansen

Field Regions



2019 NRL Space Solar Study Summary Recommendations

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(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

Power Beaming Applications

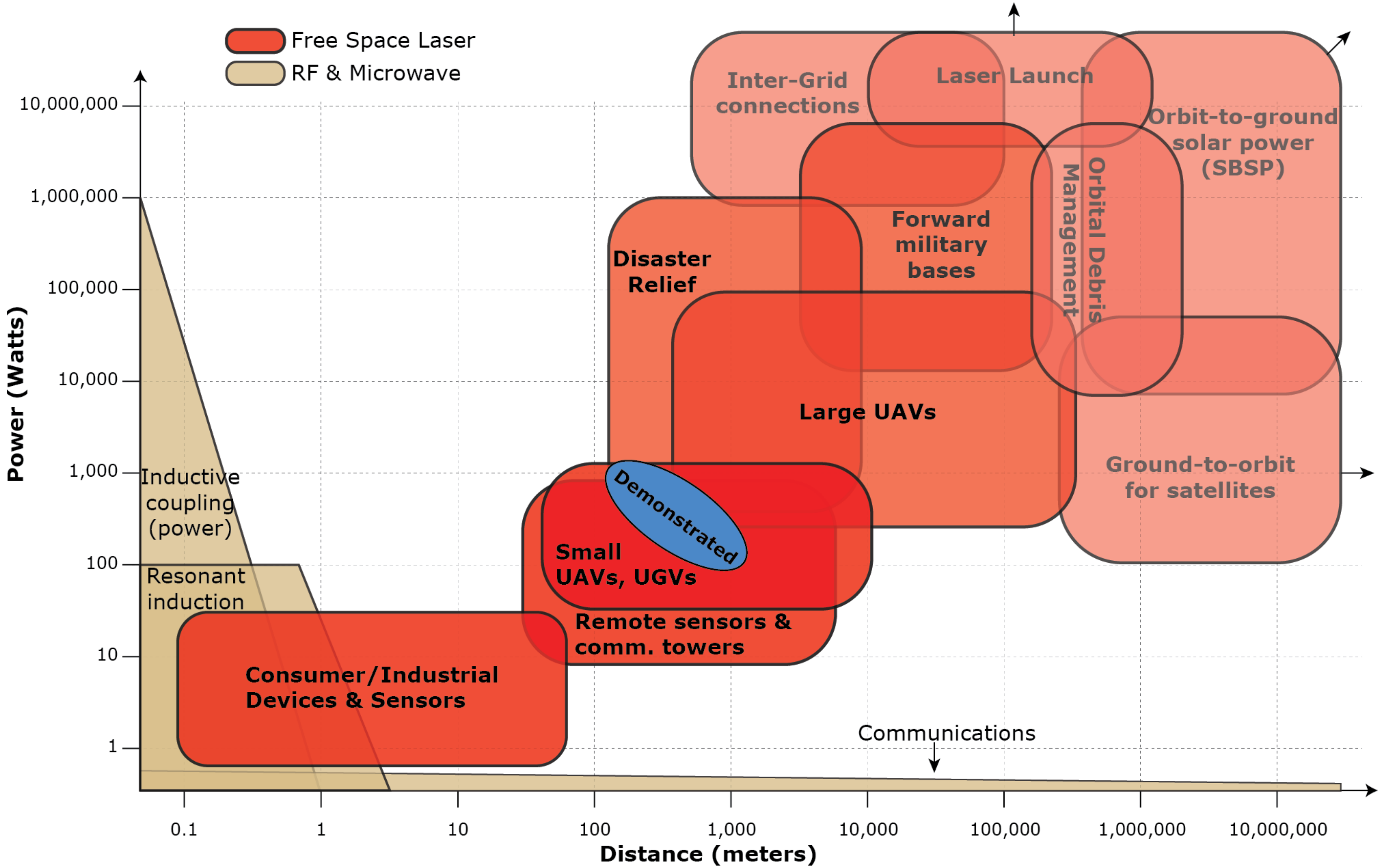

Figure credit: PowerLight (formerly LaserMotive)

Attenuation of EM Waves By The Atmosphere

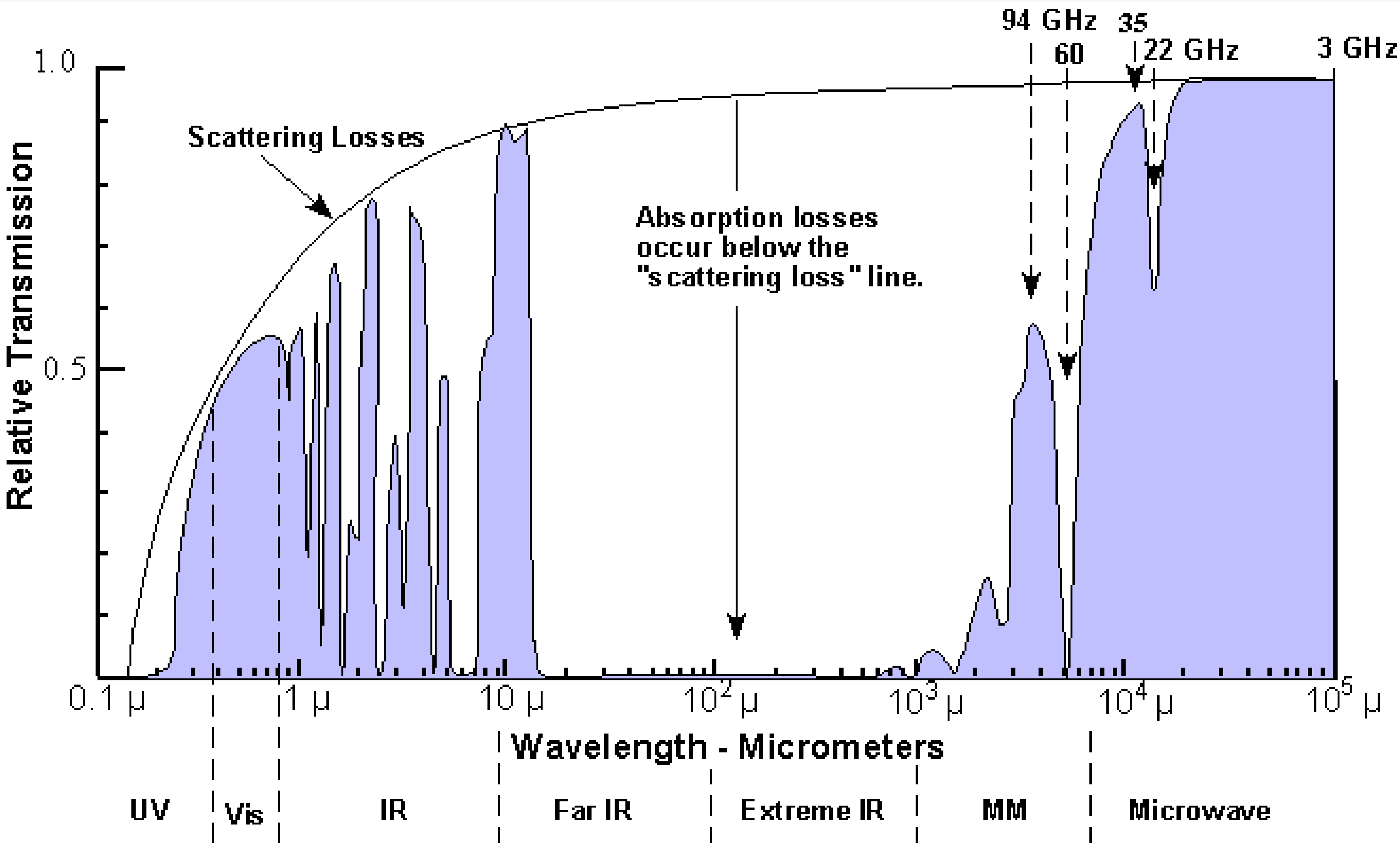

Figure from https://upload.wikimedia.org/wikipedia/commons/7/78/Atmosph%C3%A4rische_Absorption.png