Co-orbiting/Formation Flying with ISS & Other Customers

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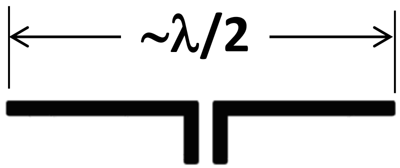
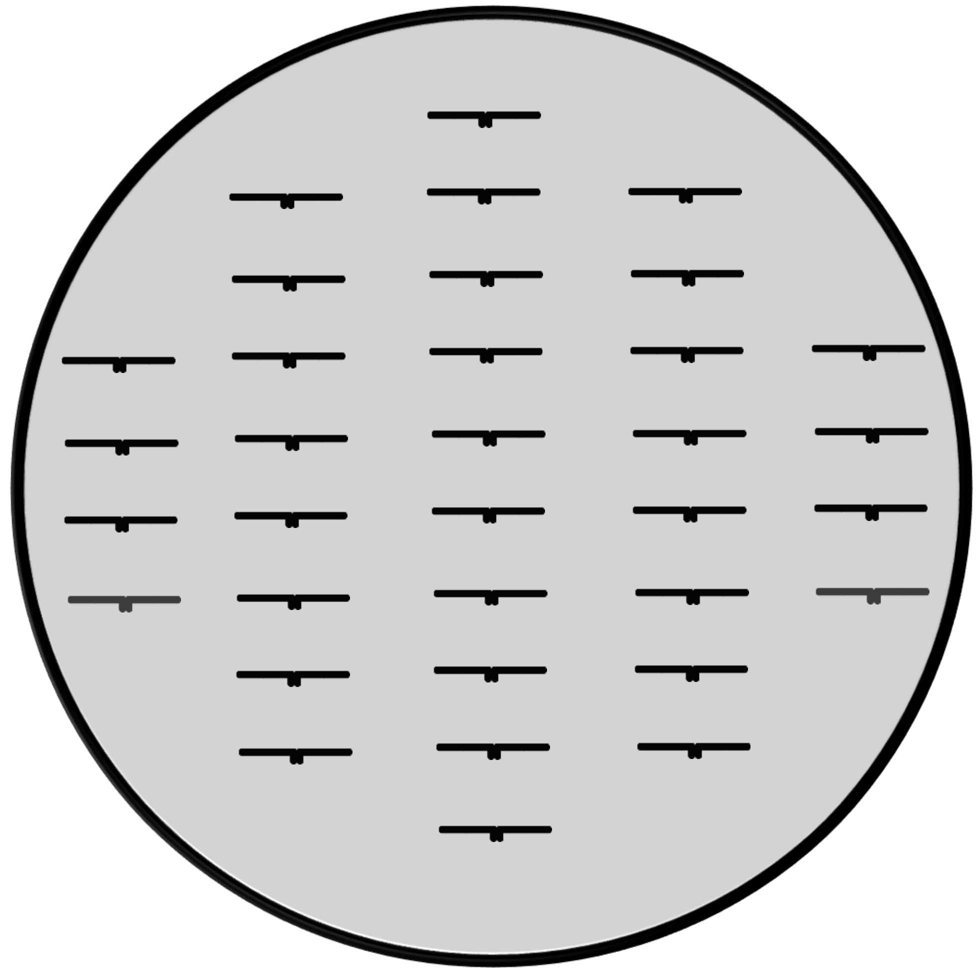
Introduction

- The path to commercial space-based solar power systems may involve addressing early high-value markets where premium prices will be competitive, such as:
  - Satellites and other assets in low Earth orbit where drag due to solar arrays may make higher effective area power densities preferable
  - Satellites whose solar cells become degraded toward the end of their lives
  - Satellites whose mass constraints may make higher duty cycle power reception preferable to high-capacity storage batteries
- Power utility satellites have been proposed to meet these needs
- The International Space Station may serve as a testbed for such a capability, and may even provide operational power to free-flying client satellites in the near term

Phased Array Transmitting Antenna: Notional Design



- A phased array transmitting antenna consists of many dipole or slotted waveguide elements, each about a half wavelength long
- By varying the current to the elements, a desired energy distribution at the target can be achieved
- The beam can also be steered by varying the phase of the elements



Far Field vs. Near Field

- As the terms imply, near field refers to the region near the transmitting antenna; far field refers to the region far from the transmitting antenna
- The laws of diffraction manifest themselves in the far field
- No hard-and-fast boundary, but it is generally considered to be the Fraunhofer distance d_f:

$$d_f = \frac{2\,D_t^{\,2}}{\lambda}$$

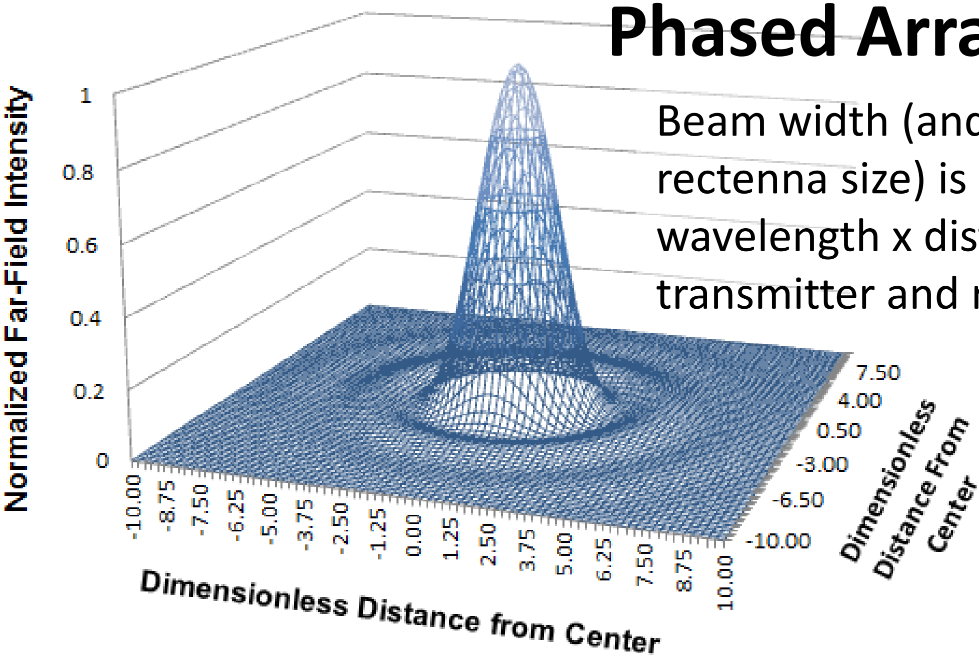
where

D_t = transmitting antenna array diameter

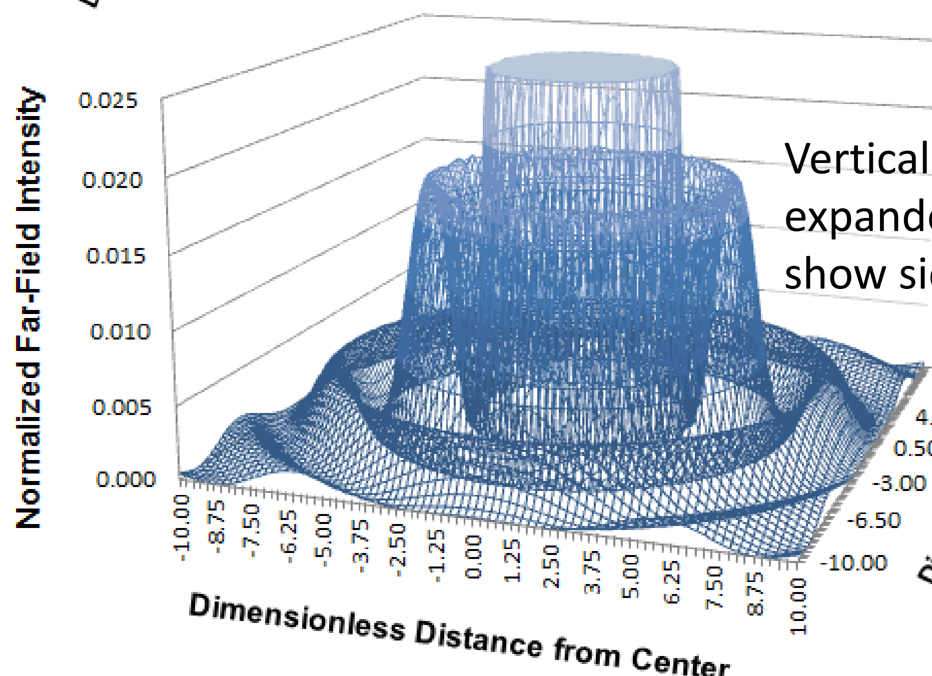
λ = wavelength

- For a classic solar power satellite having a transmitter diameter of 1000 meters and a wavelength of 12.24 cm, d_f = 16,700 km, so for a geostationary SPS at 36,000 km, Earth is in the far field
- Far field wireless power transmission uses electromagnetic waves at radiofrequency, microwave, millimeter wave, infrared, or optical wavelengths

Energy Distribution from a Uniformly Illuminated Phased Array Antenna



Beam width (and hence required rectenna size) is proportional to wavelength x distance between transmitter and receiver



Vertical scale expanded to show sidelobes

Power Beaming Constraints

- For efficient beam capture, the following condition must hold

$$\frac{D_t D_r}{\lambda x} = \text{constant}$$

where

D_t = transmitting antenna array diameter

D_r = rectifying receiving antenna array (rectenna) diameter

λ = wavelength of beam

x = distance between transmitting antenna and rectenna

- The value of the constant depends on the transmitting antenna energy pattern and the desired capture efficiency
  - For a uniform energy distribution at the transmitter, the constant will have a value of 2.44 for capture of the entire main beam lobe, which contains 84% of the energy
- The geometry of ISS will constrain D_t
- The geometry and mass of the free flyer will constrain D_r
- Orbital mechanics will constrain x
- These constraints will change for future power beaming and receiving satellites
- Therefore, λ must be allowed to "float"; hence, an ISS demo must be frequency-agnostic to be extensible to a variety of future clients

Satellite Specifications

Satellite	Typical Mission	Typical Orbit	Mass at Launch (kg)	First Customer	Power Level (kW)	Reference
Boeing 702 HP	Communications	GEO	5400-5900	PanAmSat Corp.	>12	http://www.boeing.com/space/boeing-satellite-family/
Boeing 702 MP	Communications	GEO	5800-6100	Intelsat	6 to 12	http://www.boeing.com/space/boeing-satellite-family/
Boeing 702 SP	Communications	GEO	1500-2000	Asia Broadcast Satellite	3 to 8	http://www.boeing.com/space/boeing-satellite-family/
Boeing 702 HP GEM	Communications	GEO	1500-2000	MEXSAT	8 to 10	http://www.boeing.com/space/boeing-satellite-family/
Boeing 502			1000		1.5	http://www.boeing.com/space/boeing-satellite-family/
Lockheed Martin AEHF	Military Communications					http://m.lockheedmartin.com/us/products/advanced-extremely-high-frequency--aehf-.html
International Space Station	Research	LEO	419,725		84 -120	https://www.nasa.gov/mission_pages/station/structure/elements/solar_arrays.html
Hubble Space Telescope	Research	LEO	11,110		~2.1 average	http://hubble.stsci.edu/the_telescope/hubble_essentials/quick_facts.php

Client Satellite Orbits

Altitude (km)	Orbital Period (hours)	Shadow Duty Cycle (fraction)	Time in Shadow (hours)	Comments
200	1.47	0.421	0.621	
350	1.53	0.397	0.605	ISS
540	1.59	0.373	0.594	Hubble
1,000	1.75	0.332	0.582	
1,500	1.93	0.300	0.581	
2,000	2.12	0.275	0.584	
5,000	3.36	0.189	0.636	
20,200	11.98	0.077	0.924	GPS
35,786	23.93	0.048	1.157	GEO at equinoxes

- Maximum fraction of time in shadow varies greatly, but is a fairly consistent half hour to hour, typically ~36 minutes
  - For non-equatorial orbits, time may be shorter if line of nodes of orbit not aligned with sun vector
- To be investigated: can a common power supplying satellite, operating in collect-store-transmit mode be designed for multiple orbits, with individual units deployed in particular orbits?
- First step in investigation: demonstrate power beaming from ISS to a free-flyer

Power Transmission Modes

Order-of-Magnitude Distance	Power Transmission Mode / Wavelength	Pros	Cons
Contact	Conduction	Most efficient	Requires rendezvous & docking w/each client; hence, extensive redesign of client
Meters	Inductive or magnetic coupling	Highly efficient	Requires rendezvous w/each client; possible EMI
10's - 100's of meters	Full spectrum lamp	Little or no redesign of client; minimal EMI	Less efficient; requires rendezvous
Up to 10's of km	Microwaves	Highly efficient; extensible to full-scale SSP	Requires some redesign of client; ΔV required to serve multiple clients; possible EMI
Up to 100's of km	Millimeter waves	Efficient; extensible to full-scale SSP	Requires some redesign of client; ΔV required to serve multiple clients; possible EMI
Up to tens of 1000's of km	Lasers (IR or optical)	Can serve multiple clients without changing orbits, modest redesign of client, depending on choice of wavelengths; minimal EMI	May be less efficient, unless laser matched to solar array bandgap; treaty/legal/weaponization issues

Approach to ISS Power Beaming Demonstration and Operations

- The investigation will involve three phases:
  1. ISS as a testbed beaming power to a microsatellite (e.g., a 6U CubeSat)
  2. ISS beaming operational power to small satellites
  3. Transition to a more general Cislunar Surface-to-Surface Power & ancillary services Beaming (SSP&asB) capability

- For Phases 1 and 2, consider the following frequencies:
  - 2.45 GHz
  - 5.8 GHz

    } Excessive beam divergence for space-to-space applications, but good atmospheric penetration for space-Earth beaming

  - **26.5 GHz (low Ka band)**
  - **36 GHz (high Ka band)**
  - **~95 GHz (W band)**

    } Most promising for space-to-space in the near term; proposed for further study

  - ~1 μm wavelength (near IR or optical)

    } Lower efficiency and weaponization fears, but less beam divergence may make it worth considering for longer distances in the far term; also possible compatibility with solar arrays

- A frequency-agnostic approach to Phases 1 and 2, combined with lessons learned from ISS rendezvous and docking and other cislunar missions will provide extensibility to Phase 3

Free Flyer Co-orbiting with ISS

Maximum Beaming Distances

Transmitting antenna 1642 cm^2 area (0.46 m diameter)

Rectenna 1 m diameter

Frequency (GHz)	Wavelength	Approx. Near Field Boundary (m)	Diffraction-Limited Distance [84% capture] (m)	Max Distance (m) for 50% Capture (m)	Capture Efficiency at 200 m	Capture Efficiency at 400 m
2.45	12.24 cm	3	1.5	3.5	0.02%	0.01%
5.8	5.17 cm	8	3.6	8.3	0.12%	0.03%
26.5	11.31 mm	37	16.6	38	2.5%	0.6%
36	8.33 mm	50	22.5	52	4.5%	1.2%
95	3.16 mm	133	59	136	27.6%	7.8%
245	1.22 mm	342	153	351	81%	41%
3.00.E+05	1.00 µm	418,132	187,392	429,384	100%	100%

- Shaded cases are proposed for ISS demo
- Green distances are in near field, so numbers shown are somewhat pessimistic – however, scanning losses are not accounted for
- Lasers at optical or IR wavelengths may be able to beam to clients in different orbits without changing orbit
- Microwaves and millimeter waves may require orbital transfer of power supplying satellite to serve multiple client satellites

Maximum Beaming Distances

Transmitting antenna 10,000 cm^2 area (1.13 m diameter)

Rectenna 1 m diameter

Frequency (GHz)	Wavelength	Approx. Near Field Boundary (m)	Diffraction-Limited Distance [84% capture] (m)	Max Distance (m) for 50% Capture (m)	Capture Efficiency at 200 m	Capture Efficiency at 400 m
2.45	12.24 cm	21	3.8	8.7	0.13%	0.03%
5.8	5.17 cm	49	8.9	20.5	0.73%	0.18%
26.5	11.31 mm	225	40.9	94	14.2%	3.8%
36	8.33 mm	306	55.5	127	24.6%	6.8%
95	3.16 mm	807	147	336	79.9%	38.7%
245	1.22 mm	2081	378	866	91%	84%
3.00.E+05	1.00 µm	2,546,479	462,450	1,059,642	100%	100%

- Shaded cases are proposed for ISS demo
- **Green** distances are in near field, so numbers shown are somewhat pessimistic – however, scanning losses are not accounted for
- Lasers at optical or IR wavelengths may be able to beam to clients in different orbits without changing orbit
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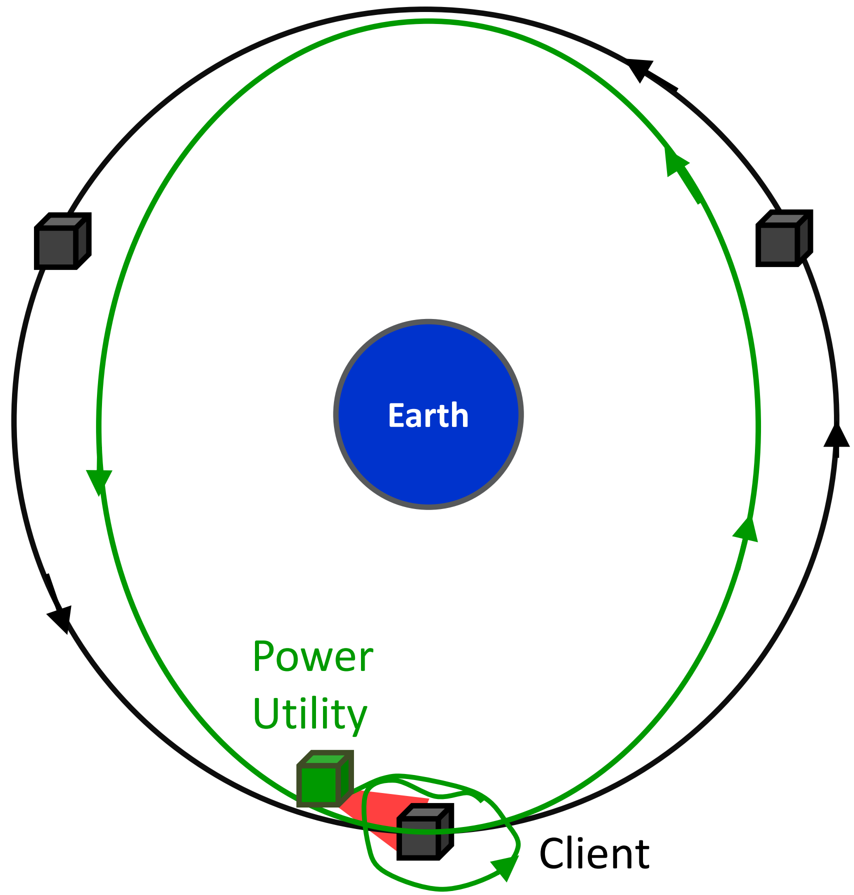
Power Densities at Rectenna for ISS Demo

	Power Density (Watts/cm^2)	Power Density (Watts/cm^2)	Power Density (Watts/cm^2)
	P_d	**P_d**	**P_d**
	Case 1 @26.5	**Case 2 @36 GHz**	**Case 3 @95 GHz**
Table 1. Power Density with D=200 m, P_t = 3000 W and A_t = 1642 cm^2	0.00964	0.01774	0.12331
Table 2. Power Density with D=200 m, P_t = 6000 W and A_t = 1642 cm^2	0.01929	0.03549	0.24661
Table 3. Power Density with D=200 m, P_t = 3000 W and A_t = 10000 cm^2	0.05874	0.10809	0.75108
Table 4. Power Density with D=200 m, P_t= 6000 W and A_t = 10000 cm^2	0.11747	0.21617	1.50216

I_{sc} = *Solar Constant at 1 AU = 0.1367 Watts/cm2*	P_d significantly lower than I_{sc}
	P_d similar to I_{sc}
	P_d significantly higher than I_{sc}

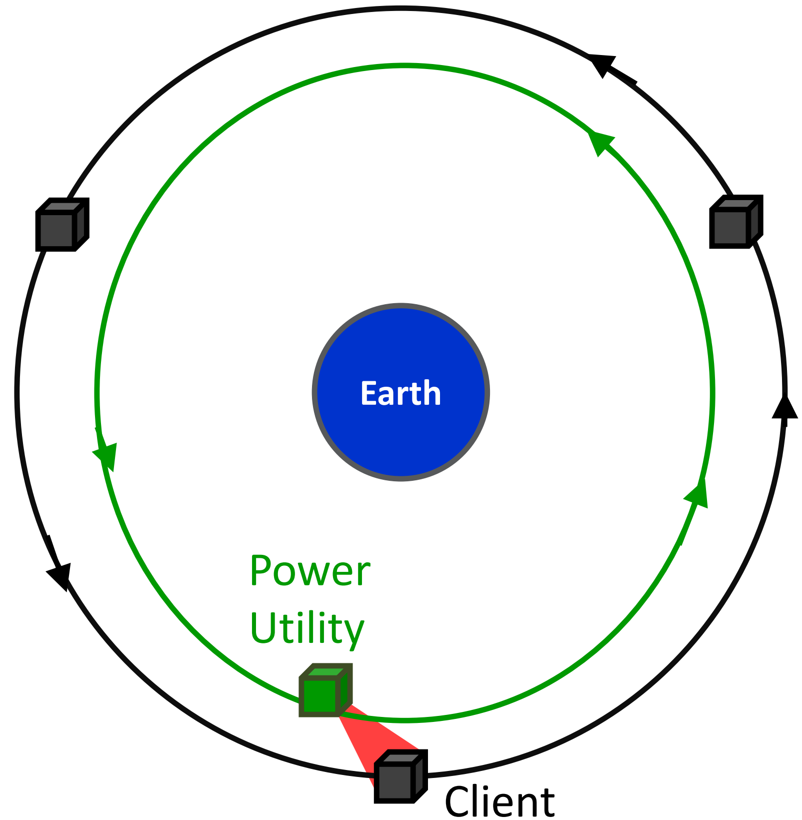
Scenario A: Proximity

- Dock for direct conductive connection
- Close rendezvous for inductive coupling
- **Demo mission: Co-orbit in a "halo" or lead at a distance of at least 200 meters (considered here and proposed for ISS demo)**
- For operational missions, service client, then move on to next client in same orbital plane



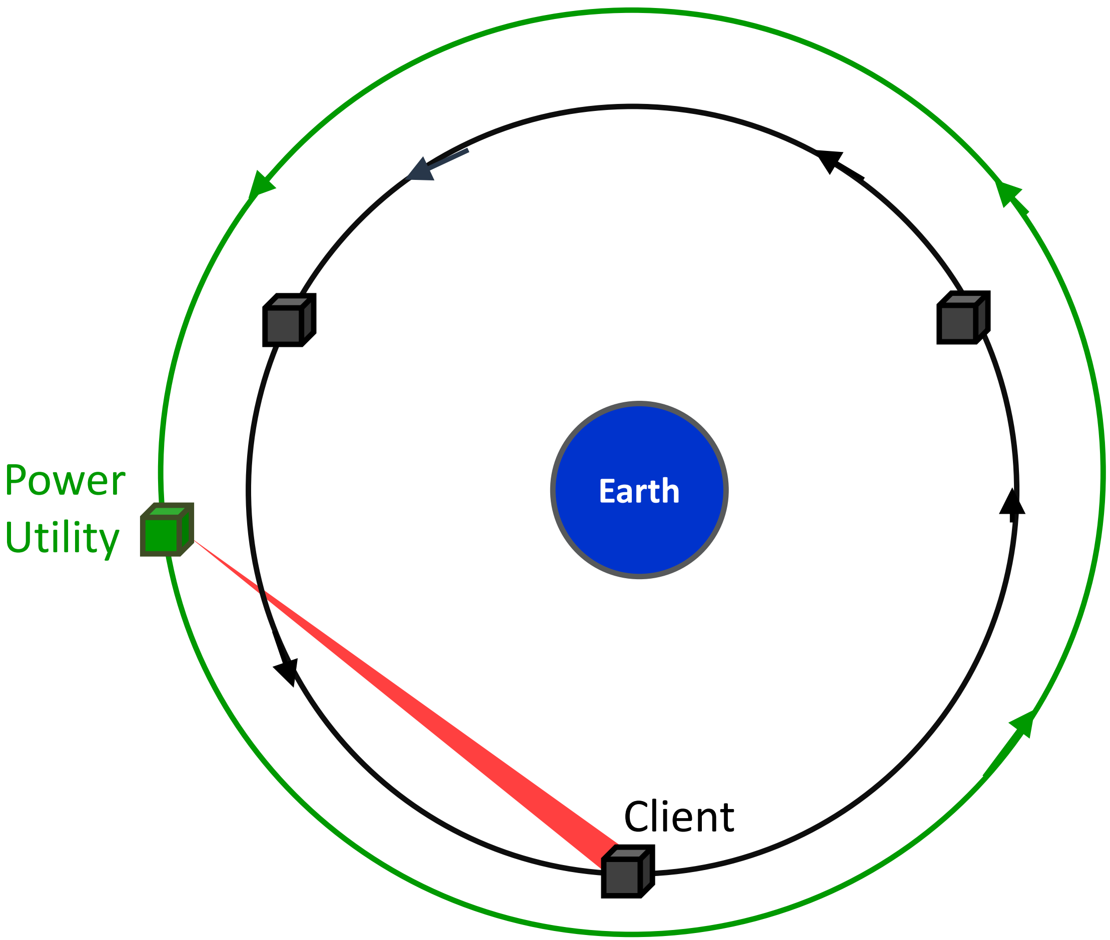
Scenario B: Flyby

- No rendezvous; power utility is in a slightly lower, or slightly higher orbit than client
- Wavelength: mm waves or shorter
- Service client during flyby, then move on to next client
  - Client likely in same plane
  - However, may be able to propagate from one plane to another with similar inclinations by differential nodal regression, if orbital elements are properly chosen
- Unlikely to meet constraints of an ISS demo due to limits on close ISS flyby, but Scenario A can serve as proxy to this for demo purposes



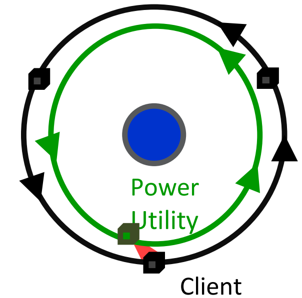
Scenario C: Beam Slewing

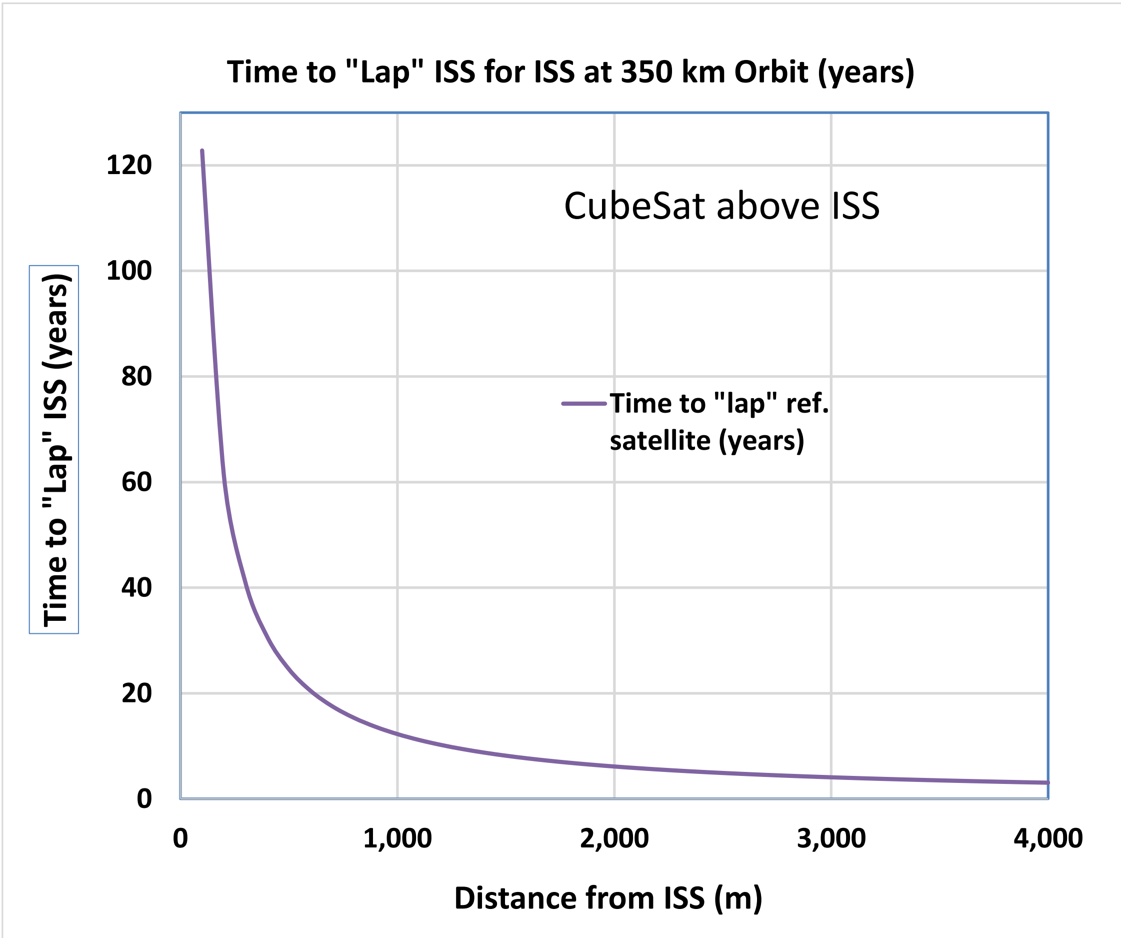
- Orbit transfer not needed
- Beaming distance: hundreds of km (perhaps up to thousands)
- Service client, and move on to next client, by beam slewing
- Wavelength: infrared or optical
- Can take advantage of orbital motion to extend contact time and minimize beam divergence; however, proximity operations are probably not needed
- Not practical for ISS demo, but may be demo'ed in the future if legal and weaponization issues of laser WPT in space are addressed



Scenario B: Flyby – Impractical for ISS Demo

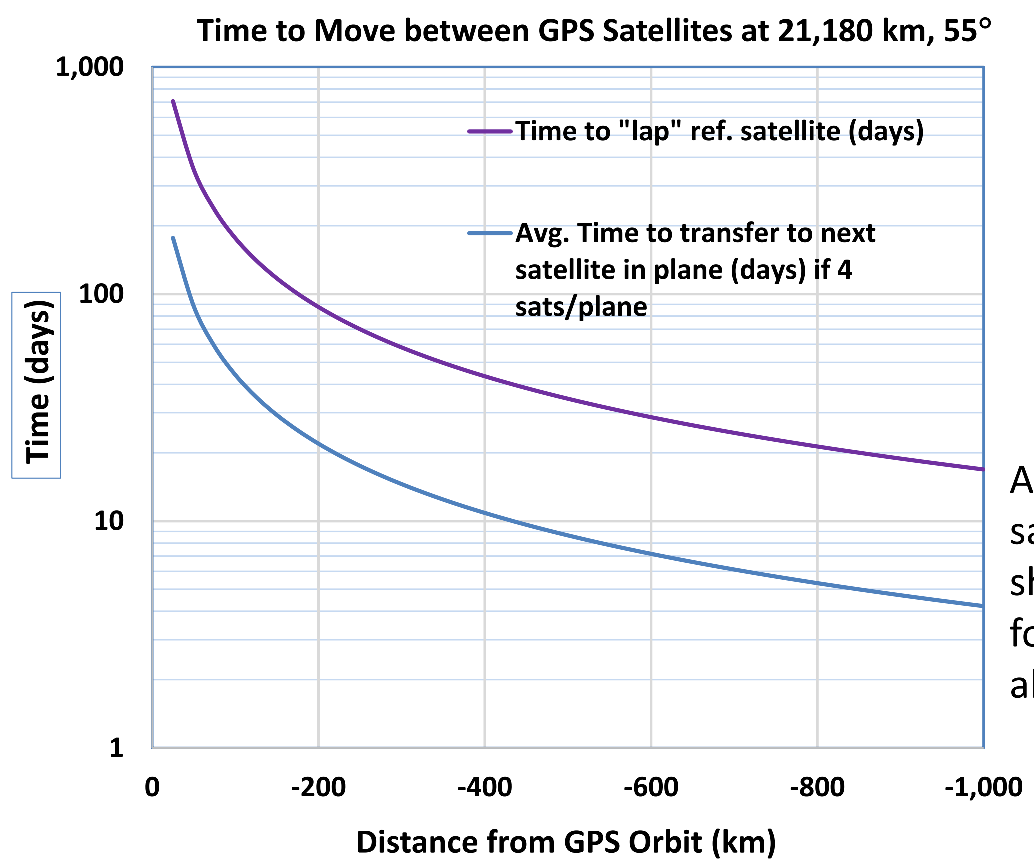
- Possible safety issue of flying through 4 km x 2 km x 2 km ISS Approach Ellipsoid
- Time to "lap" ISS is too long
  - Analysis virtually identical for client satellite above or below ISS for small differences in altitude between the two

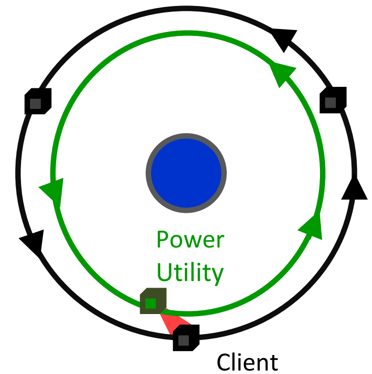




Scenario B: Flyby – May be practical for client at GPS alt.

- Nominal constellation: at least 24 satellites in 6 planes in a 20,180 km, 55° circular orbit
- A given power satellite could be assigned to one orbital plane (differential nodal regression is low; would take decades or longer to precess to next plane)
- Transfer time within a plane is an average, since GPS satellites are not evenly spaced within a plane

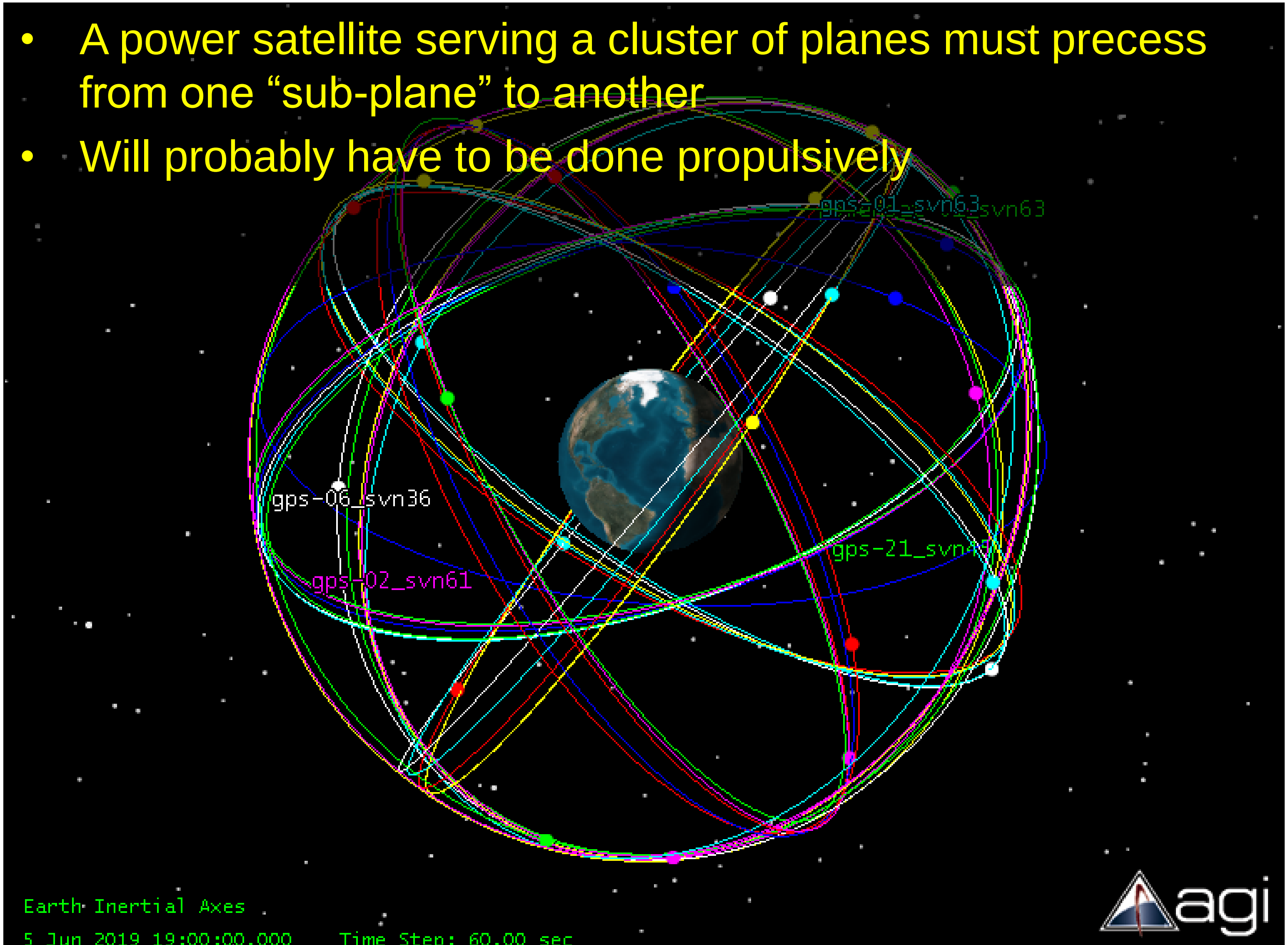




Altitude of power satellite below GPS is shown. Results similar for power satellite above GPS.

More Realistic GPS Constellation: Clusters of Orbital Planes

- A power satellite serving a cluster of planes must precess from one "sub-plane" to another
- Will probably have to be done propulsively



Conclusions

- A power beaming demonstration involving ISS beaming to a free flyer is feasible
- This can be extended to operational power for small free flying satellites around ISS
- This is extensible to power satellites beaming to higher power clients in other orbits, but more research is needed
  - Need to determine more specific requirements; assess electrical and thermal limits on space-based WPT; beam contact times, as determined by orbital motion; etc.
- Such a utility can serve as a set of transitional steps toward a large-scale cis-lunar space solar power system, and eventually, to supplying energy to Earth

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  - *Space Mission Engineering: The New SMAD, edited by James R. Wertz, David F. Everett, and Jeffery P. Puschell*
  - AGI (creators of STK)

References (1/2)

1. Skolnik, Merrill I. (1980) *Introduction to Radar Systems*, Second Edition, McGraw-Hill, New York.

2. Glaser, Peter E. (1968) "Power from the Sun: Its Future," *Science*, Volume 162, Number 3856, 22 November, pages 857-861.

3 Peterson, M.N.A., Criswell, D.R., Greenwood, D.R., and Waldron, R.D., 1993, "Progress and Plans for a Lunar Power System," *Proceedings of the Third Annual World Energy System Symposium*, Uhzgorod, Ukraine, November.

4 Maccone, Claudio (1995) "Solar Foci Missions," Proceedings of "Practical Robotic Interstellar Flight: Are We Ready?" conference held at New York University, August 29 - September 1, 1994; British Interplanetary Society, in press.

5. Maccone, Claudio, and Gregory L. Matloff (1994) "SETIsail: A Space Mission to 550 AU to Exploit the Gravitational Lens of the Sun for SETI and Astrophysics," *Journal of the British Interplanetary Society*, Vol. 47, pp. 3-4.

6. Potter, Seth D., and Gregory L. Matloff (1995) "Light Sail Propulsion Using Thin-Film Photovoltaic Technology," *Proceedings of "Practical Robotic Interstellar Flight: Are We Ready?"* conference held at New York University, August 29 - September 1, 1994.

7. Potter, Seth D. (1992) "Microwave Power Transmission Using Tapered Beams," *Space Power*, Volume 11, Number 2, pages 155-174.

8. Potter, Seth D. (1993) "Optimization of Microwave Power Transmission from Solar Power Satellites," doctoral dissertation, New York University Department of Applied Science, May.

9. Suddath, Jerrold H. (1980) "Solar Power Satellite (SPS) Microwave Antenna System," NASA Johnson Space Center Memorandum, EH2-80-104.

10. Potter, Seth D. (1994) "Analytic Integration of a Common Set of Microwave Beam Intensity Functions," *Space Power*, Volume 13, Numbers 3 and 4, in press.

11. Chang, K., J.C. McCleary, and M.A. Pollock (1989) "Feasibility Study of 35 GHz Microwave Power Transmission in Space," *Space Power*, Volume 8, Number 3, pages 365-370. (Presented at the International Astronautical Federation - International Conference on Space Power, Cleveland, Ohio, 5-7 June 1989.)

12. Kreyszig, Erwin, 1983, *Advanced Engineering Mathematics*, Fifth Edition, John Wiley and Sons, New York.

References (2/2)

13. Lin, Jenshan, "Wireless Power Transmission: From Far-Field to Near-Field", University of Florida Gainesville, Florida USA. Presentation to IEEE MTT Society, http://ewh.ieee.org/r8/norway/ap-mtt/files/Lin_WPT.pdf.

14. Potter, S., Walker, H., and Powell, J., "Mathematics of Beam Forming for Near and Far Field Power and Propulsion", presentation given at the International Space Development Conference, San Juan, Puerto Rico, 18-22 May 2016.

15. MIL-STD-464, Rev. C, Department of Defense Interface Standard, *Electromagnetic Environmental Effects: Requirements for Systems*, http://http://everyspec.com/MIL-STD/MIL-STD-0300-0499/MIL-STD-464C_28312/

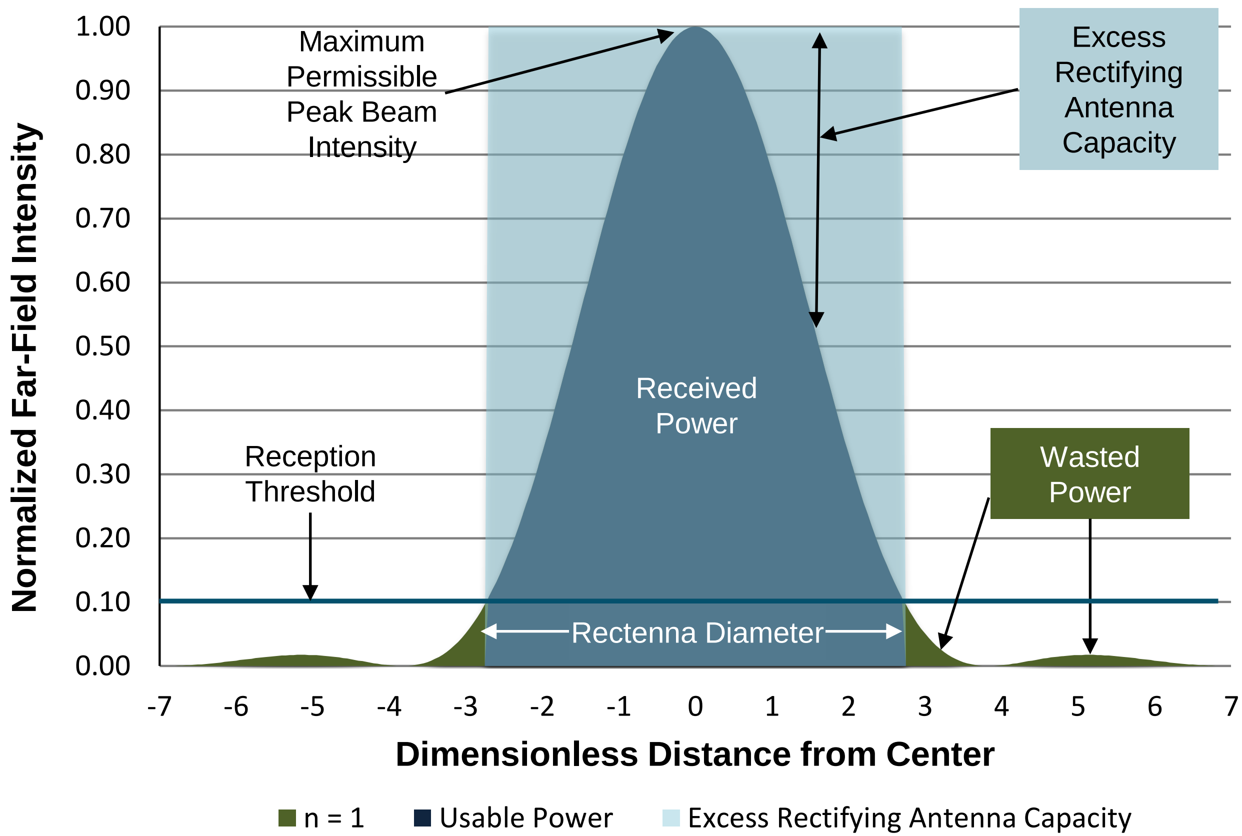
16. Wertz, James R., Everett, David F., and Puschell, Jeffery J., *Space Mission Engineering: The New SMAD*, Microcosm Press, 2011.

17. Potter, Seth D., "Opportunities and Constraints for Wireless Power Transmission", presentation given at the International Space Development Conference, St. Louis, MO, 25-29 May 2017.

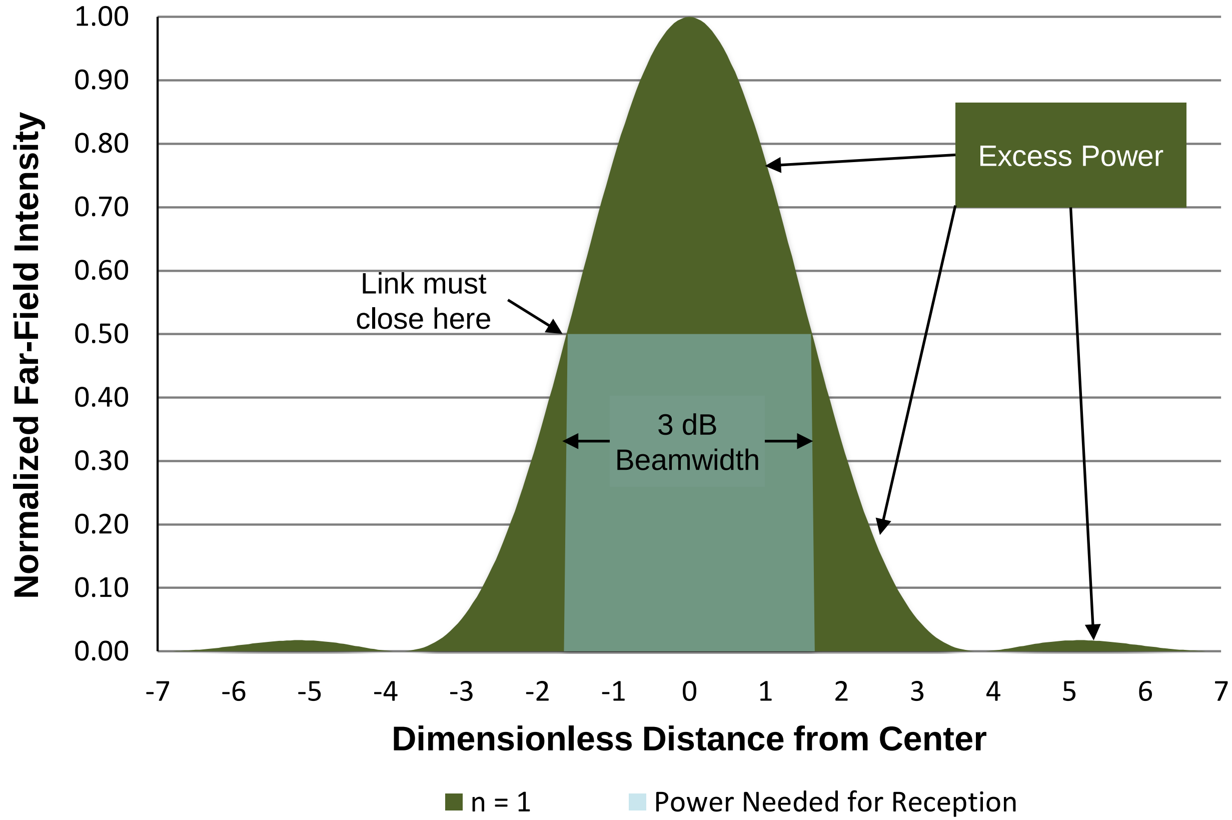
18. Barnhard, Gary P., and Potter, Seth D., "Challenges of Space Power Beaming: Forging Production Services from the Technology Development Trade Space", IAC-18-C3.2.4.

Backups

Implications for Systems Architecture: Wireless Power Transmission



Implications for Systems Architecture: Communication



- Communication systems are typically (but not always) designed to close the link at the 3 dB (half-power) beamwidth
- Optimum beam shape may be a "flat top" – a limiting case, not fully achievable in practice