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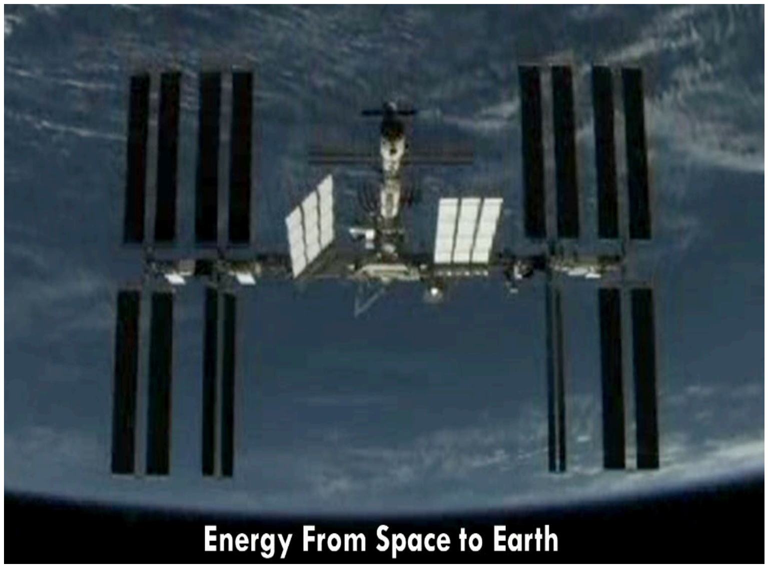

Multi-Nation WPT Demonstration Experiments

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Multi-Nation WPT Demonstration Experiments

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ABSTRACT

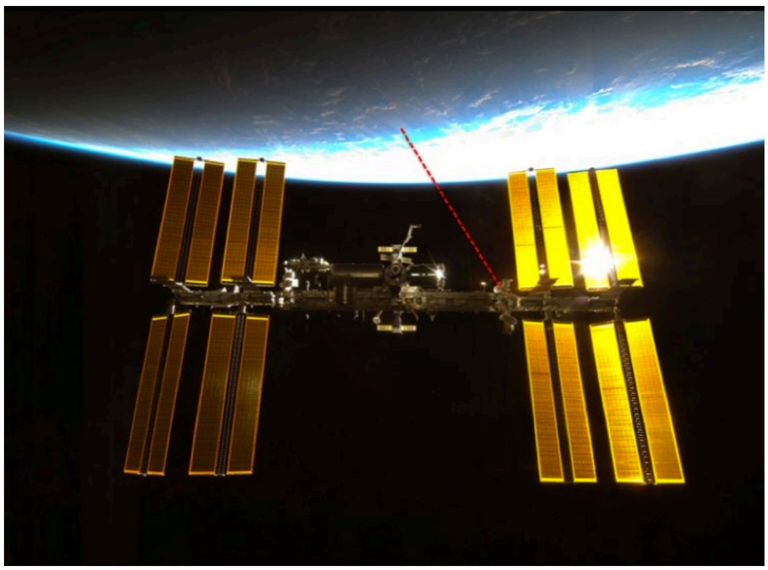
A project originating with Georgia Institute of Technology is described in which the International Space Station (ISS) serves as an experimental platform for the relay of energy from space to earth. The multi-nation test will feature the transmission of small amounts of solar-generated electric power from the ISS using millimeter waves, for the purposes of collecting atmospheric propagation data and testing technologies for power beaming, aiming, and reception. This initiative represents an early first-step towards installation of a global Space Solar Power Grid emphasizing international collaboration, synergy with the terrestrial energy industry and with retail power beaming markets. The technical paper on which this visualization is based is listed in References below.

Five-Nation 2013 from Space Journal on Vimeo.

TECHNICAL BRIEF

The objectives of this experiment are to:

1. Demonstrate safe generation and transmission of 220 GHz beams from the International Space Station;
2. Obtain data on pointing error to various locations on Earth over a 90 degree azimuth, through day-night and seasonal variations;
3. Obtain data on beam spread at 220 GHz to locations worldwide.
4. Obtain data on beam attenuation at 220 GHz to locations worldwide under different atmospheric conditions; correlate with meteorological data, and
5. Set up template for international collaboration re. space solar power.



The in-space experiment will include:

- 1 kWe millimeter wave generator, amplifier, waveguide link and thermal control system, in Express Logistics Container (ELC), Antenna-Waveguide in second ELC for deployment using manipulator arm;

- 2m x 2m transmitting antenna pointing downward from a truss location (S3/P3 nadir), or from a Columbus ELC point. Clear view for phase-array beam sweep 45 degrees fore and aft, and 10 degrees side to side;

- Ground stations co-located with solar power plants wherever possible. Candidate locations are frequently under the ISS orbital path;

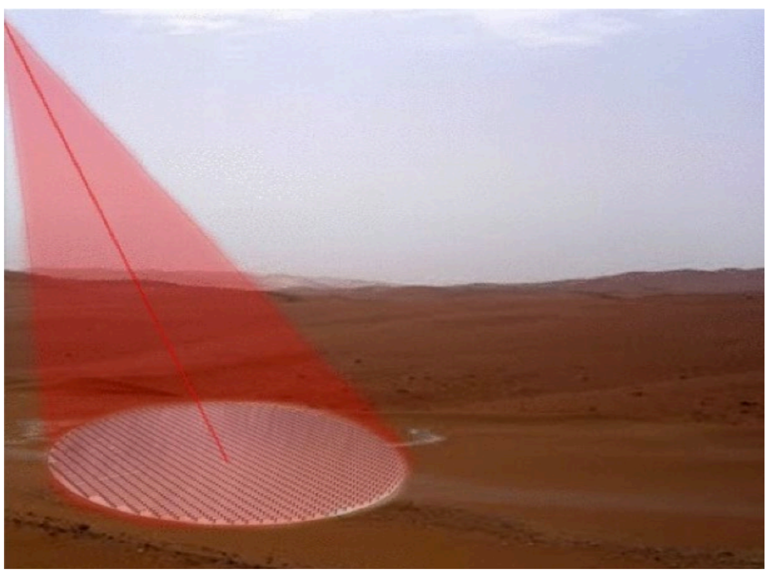
- Collect data on beam aiming, link quality, weather, atmospheric attenuation, spillover and efficiency for 3 years; and

- Fine-tune frequency for best transmission, if possible.

The ground experiments will include: - Bench-scale development of 220GHz generation, amplification, transmission, reception, reconversion;

- Increase distance: bench, long waveguide, ceiling, pole, tethered aerostat, waveguide to aerostat, aerostat-ground, aerostat-aerostat, aerostat-balloon; - Increase power: Effect of beam on air, tunneling through moist air; and

- Frequency optimization.



Experiment basic requirements/expectations

1. Delivery to ISS by vehicle of the SpaceX Dragon class.

2. Retrieval, attachment and deployment by ISS manipulator arm.

3. Power: 1 kW DC power input; 100 watts cw 220 GHz waveguide output.

4. Beam shall point anywhere within 45 degrees forward, sweep steadily to 45 degrees aft, and/or 10 degrees to port or starboard.

5. Unobstructed visibility from the transmitting phase-array antenna.

6. Accuracy of 10 meters CEP at ground target achieved within 10 orbits.

7. Low-power laser link activate along main power beam path.

8. Beaming cutoff within 1 millisecond of link loss; Re-activate only by reset.

9. Continuous data exchange to operate immediately prior to, during and following power transmission, between the ISS system and ground receiver facility.

10. Simultaneous communications with 5 stations plus controller.

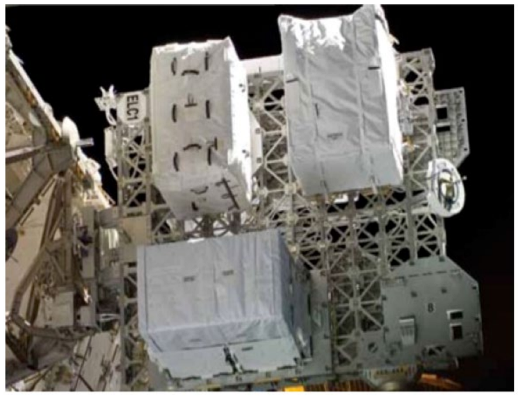
Power Budgets, Initial and Final

1 kW DC, accessed through two 500-watt ELC attachments.
DC-220GHz efficiency assumed = 220GHz-DC
Target transmission efficiency 80-90% *; capture 94%.

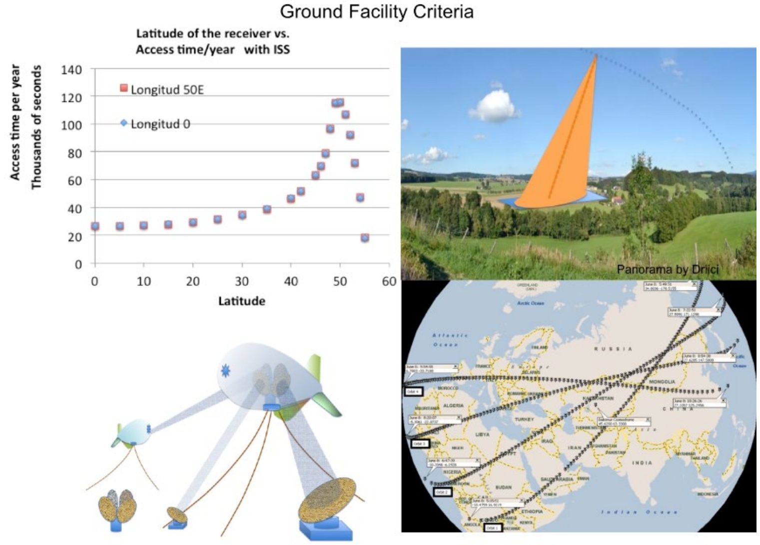
Technology	Efficiency	TRL	ATC , W (sized to 1KW)	Received power, W	Converted power, W
Gyratron	10%	**3-5**	900	75	7.5
Solid State MMIC	90%	**0-1**	100	761	685

* Assumes aerostat-waveguide or aerostat DC conversion at receiver

Payload integration, delivery, deployment and recovery



Ground Facility Criteria



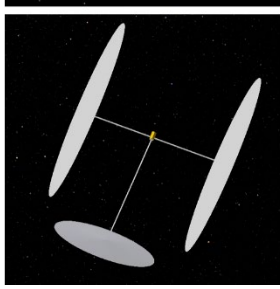
Ground Facility: Example Suggestions

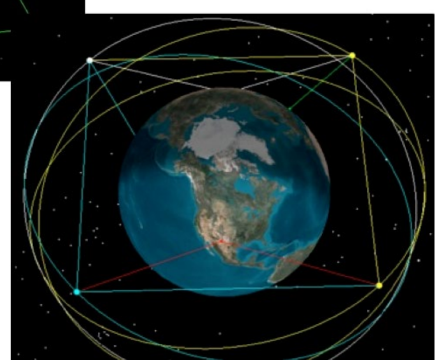
Nation	Area	No./Yr	Mean, sec.
USA	Mojave desert	381	82
Argentina	Santa Cruz	1017	98
Spain	Sevilla	406	83
South Africa	Kalahari Desert	316	86
Saudi Arabia	Arabian Desert	277	84
Kazakhstan	Qaraghandy	852	81
India	Ambani Solar Park	310	84
China	Golmud, Qinhai	390	83
Australia	Northern Territory	283	86

Power Exchange Experiment

Initial design may use 5000km orbits to increase dwell time, 1MW beams

As numbers of nations and satellites grow, altitude comes down to 2000km, 60MW beams





Risk

Technology

Beam Pointing
Atmospheric propagation
Waveguides
220GHz conversion
Phase array transmitter
Phase array receiver
220GHz-DC conversion
Specific power of mmwave systems

ITAR issues

Ideal Process Roadmap

1. Multinational team develops white paper; Critique by ISS, space agencies.
2. Planning document review by space agencies, agency reps appointed.
3. RFI on ISS experiment components.
4. System engineering plan detailed
5. Experiment scheduled.
6. Preliminary design review
7. Detailed design review
8. Construction and ground testing
9. Development of ground facilities
10. Launch and deployment

11. 1-year review of ISS data and issues
12. CDR, PDR of Multinational experiment
13. Ground facility development
14. Satellite construction, launches and testing
15. Mulitnational Power Exchange (MNPE)
16. Review of ISS and MNPE data and issues
17. Space Power Grid Phase 1 RFQ
18. SPG Phase 1
19. Full-scale SSP CDR, PDR
20. Runway based space launch infrastructure development
21. Full scale SSP deployment

ECONOMIC CONSIDERATIONS

When Space-based solar power provides the 4 to 8 TWe needed to replace terrestrial fossil primary electric power, we can expect to see a constellation of 4000 to 8000 satellites in space orbit, each delivering on the order of 1 Gigawatt of electric power (1GWe) to the terrestrial power grid. Looking up from any point on Earth, one should expect to see one or two of these satellites within one's range of vision at any time. Most nations will be participants and partners, even more than with today's communications satellites.

The massive global investment needed for this enterprise will require a commercially viable, revenue-generating progression. We can expect significant advances to have occurred before the risks, superstitions and other obstacles will have been systematically confronted, overcome or circumvented. Numerous architecture options have been proposed. This experiment is a necessary first-step in the direction of an eventual solution to making energy from space a profitable operation.

Space Solar Power is within reach. The primary uncertainties at the moment are in the generation and beaming of millimeter wave power. The next-step proposed is a multinational experiment where up to 6 waveguide satellites are placed in orbit. Beamed power will be exchanged between different parts of Earth through Space, modeling, demonstrating and refining real-time power exchange that will enable renewable power plants on Earth to radically improve their business prospects. This is the starting point of the Space Power Grid.

REFERENCES

1. P. Glaser, "Power from the sun: It's future," Science, vol. 162, pp. 856–861, 1968.

2. A. Clarke, “Extraterrestrial relays,” Wireless World, vol. 51, no. 10, pp. 305–308, 1945.
3. P. Glaser, “Solar power from satellites,” Physics To- day, vol. 30, p. 30, 1977.
4. NASA, “The final proceedings of the solar power satellite,” NASA, Program review NASA-TM- 84183, 1984.
5. M. Stancati, “Space solar power, a fresh look feasi- bility study, phase 1,” NASA contract, 1996.
6. I. Bekey and R. Boudreault, “An economically vi- able space power relay system,” Acta astronautica, vol. 44, no. 7, pp. 385–390, 1999.
7. A. Meulenberg and P. Karthik Balaji, “The leo archipelago: A system of earth-rings for com- munications, mass-transport to space, solar power, and control of global warming,” Acta Astronautica, vol. 68, no. 11, pp. 1931–1946, 2011.
8. M. Mori, H. Kagawa, and Y. Saito, “Summary of studies on space solar power systems of japan aerospace exploration agency (jaxa),” Acta Astro- nautica, vol. 59, no. 1, pp. 132–138, 2006.
9. N. Nagatomo and K. Itoh, “An evolutionary satel- lite power system for international demonstration in developing nations,” in SPS 91-Power from Space, vol. 1, 1991, pp. 356–363.
10. NASA, “Space solar power, an advanced concepts study project,” NASA, NASA HQ, washington DC, NASA LeRC SSP technical interchange meeting, 1995.
11. M. Nagatomo, “An approach to develop space solar power as a new energy system for developing coun- tries,” Solar Energy, vol. 56, no. 1, pp. 111–118, 1996.
12. G. Pignolet, A. Celeste, M. Deckard, and J. Esperet, “Space solar power: Environmental questions and future studies,” Journal of Aerospace Engineering, vol. 14, no. 2, pp. 72–76, 2001.
13. L. Summerer and F. Ongaro, “Solar power from Copyright c 2013 Narayanan Komerath space: Validation of options for europe,” European Space Agency, Tech. Rep. Paper ACT-RPR-NRG- 2004-ESA, 2004.
14. T. Saiki, S. Uchida, S. Motokoshi, K. Imasaki, M. Nakatsuka, H. Nagayama, Y. Saito, M. Ni- ino, and M. Mori, “Development of solar-pumped lasers for space solar power station,” in INterna- tional astronautical congress, Fukuoka, Japan, Oc- tober 2005.
15. S. Sasaki, K. Tanaka, K. Higuchi, N. Okuizumi, S. Kawasaki, M. Shinohara, K. Senda, and K. Ishimura, “Feasibility study of tethered so- lar power satellite,” in International astronautical congress, Fukuoka, Japan, October 2005.
16. T. Saiki, S. Uchida, S. Motokoshi, K. Imasaki, M. Nakatsuka, H. Nagayama, Y. Saito, M. Niino, and M. Mori, “Development of solar-pumped lasers for space solar power station,” in 56 th International Astronautical Congress, 2005.
17. S. Potter, M. Henley, D. Davis, A. Born, M. Bayer, J. Howell, and J. Mankins, “Wireless power trans- mission options for space solar power,” in State of Space Solar Power Technology Workshop, Lake Buena Vista, Fl, October 2008.
18. S. Potter, D. Davis, and D. McCormick, “Near-term space solar power demonstrations and applications. we can get there from here,” International Space De- velopment Conference, Huntsville, USA, May 2011.
19. N. Boechler, S. Hameer, S. Wanis, and N. Komerath, “Evolutionary path towards space solar power,” in Proceedings of STAIF 2006,
20. M. E. Genk, Ed. Amer- ican Institute of Physics, 2006.

21. N. Komerath and N. Boechler, "The space power grid," in Proceedings of IAC 2006, no. IAC06- C3.4.6. International Astronautical Federation, September 2006.
22. B. Dessanti, N. Picon, C. Rios, S. Shah, and N. Komerath, "A US-India power exchange towards a space power grid," in Proceedings of ISDC 2011. Huntsville, AL, USA: National Space Society, May 2011.
23. N. Komerath, B. Dessanti, S. Shah, R. Zappulla, and N. Picon, "Millimeter wave space power grid architecture 2011," in Proceedings of the IEEE Aerospace Conference, ser. Paper 1545, no. DOI 10.1109/AERO.2012.6187078. Big Sky, Montana: IEEE, March 2012.
24. D. Criswell, "Lunar solar power system," Potentials, IEEE, vol. 15, no. 2, pp. 4–7, 1996.
25. J. Mankins, "A fresh look at space solar power: New architectures, concepts and technologies," Acta As- tronautica, vol. 41, no. 4, pp. 347–359, 1997.
26. J. Mankins, C. Miller, T. Dinnerman, D. Cheng, R. Faith, C. Linhao, W. Leary, D. Brody, M. May- field, K. Cowing et al., "The space solar power satel- lite," Aerosp. Am, vol. 35, pp. 30–36, 1997.
27. G. Landis, "Reinventing the solar power satellite," NASA, report 2004-212743, 2004. anon, "Solar power from space- european strategy in the light of sustainable development," European Space Agency, Noordwijk, Tech. Rep., 2004.
28. P. Garretson, "Solar power in space?" Strategic Studies Quarterly, Spring 2012.
29. D. Flournoy, "How is sunsat development faring in- ternationally?" Solar Power Satellites, pp. 67–78, 2012.
30. N. Geuder, V. Quaschning, P. Viebahn, F. Steinsiek, J. Spies, and C. Hendriks, "Comparison of solar ter- restrial and space power generation for europe," in 4th International Conference on Solar Power from Space–SPS, vol. 4, 2004.
31. Y. Kuroda, M. Nagatomo, and P. Collins, "Japanese perspective on power from space for earth," Space Power Resources and Manufacturing Development, vol. 11, pp. 299–302, 1992.
32. N. Komerath and P. Komerath, "Implications of inter-satellite power beaming using a space power grid," in IEEE Aerospace Conference, no. Paper P1696, Big Sky, MT, March 2011.
33. G. Hanley, Satellite power systems (SPS) concept definition study. National Aeronautics and Space Administration, Scientific and Technical Informa- tion Branch, 1980.
34. M. Henley, S. Potter, J. Howell, and J. Mankins, "Wireless power transmission options for space solar power," IAC, Tech. Rep. R.4.08, 2002.
35. F. Koomanoff and M. Riches, "Final proceedings of the solar power satellite program review," NASA TM, no. 82, p. 22676, 1980.
36. N. Komerath, V. Venkat, and A. Butchibabu, "Pa- rameter selection for a space power grid," in Space 2008, no. AIAA Paper 2008-7711, September 2008. Copyright c 2013 Narayanan Komerath
37. N. Komerath, V. Venkat, and J. Fernandez, "Near millimeter wave issues for a space power grid," in Proceedings of IASSPES2009, Huntsville, AL, USA, March 2009.
38. M. Abbasi, S. Gunnarsson, N. Wadefalk, R. Kozhuharov, J. Svedin, S. Cherednichenko, I. Angelov, I. Kallfass, A. Leuther, and H. Zirath, "Single-chip 220-ghz active heterodyne receiver and transmitter mmics with on-chip integrated antenna," Microwave Theory and Techniques, IEEE Transactions on, vol. 59, no. 2, pp. 466–478, 2011.

39. H. Essen, A. Wahlen, R. Sommer, W. Johannes, R. Brauns, M. Schlechtweg, and A. Tessmann, "High-bandwidth 220 ghz experimental radar," Elec- tronics Letters, vol. 43, no. 20, pp. 1114–1116, 2007.
40. J. Laskar, S. Pinel, D. Dawn, S. Sarkar, B. Perumana, and P. Sen, "The next wireless wave is a millimeter wave," Microwave Journal, vol. 50, no. 9, pp. 22–23, August 2007.
41. N. Komerath and A. Kar, "Retail beamed power for a micro renewable energy architecture: Survey," ACM Transactions on Embedded Computing Sys- tems, vol. 7, p. TBD, 2011.
42. N. Komerath and B. Dessanti, "Brayton cycle con- version for space solar power," in Proceedings of the 48th AIAA/ASME/SAE/ASEE Joint Propulsion Con- ference and Exhibit, no. DOI: 10.2514/6.2012-4287. Atlanta, Georgia: AIAA, August 2012.
43. M. Born, E. Wolf, and A. Bhatia, Principles of op- tics. Pergamon Pr., 1970.
44. B. Dessanti, R. Zappulla, N. Picon, and N. Komerath, "Design of a millimeter waveg- uide satellite for space power grid," in Proceedings of the IEEE Aerospace Conference, ser. Paper 1549, no. DOI 10.1109/AERO.2012.6187080. Big Sky, Montana: IEEE, March 2012.
45. N. Komerath, B. Dessanti, and S. Shah, "Millimeter- wave space power grid architecture millimeterwave space power grid architecture development 2012," Proceedings of the IEEE/AIAA Aerospace Confer- ence, Big Sky, MT, March 2013.
46. F. Deschenes and M. Nahon, "Design improvements for a multi-tethered aerostat system," in 2005 AIAA Atmospheric Flight Mechanics Conference and Ex- hibit; San Francisco, CA. American Institute of Aeronautics and Astronautics, 1801 Alexander Bell Drive, Suite 500, Reston, VA, 20191-4344, USA,, 2005, pp. 1–12.
47. S. Les Davey, R. Butler, R. Buchanan, and R. Phillips, "High altitude platform stations for aus- tralia," MONASH UNIVERSITY EPRESS, 2008. C. Lambert, A. Saunders, C. Crawford, and M. Na- hon, "Design of a one-third scale multi-tethered aerostat system for precise positioning of a radio telescope receiver," in CASI Flight Mechanics and Operations Symposium, 2003.
48. N. Komerath, A. Kar, and R. Pant, "Antenna consid- erations for retail beamed power delivery in india," in Proceedings of the 2011 International Symposium on Electronic System Design (ISED), ser. Paper No. 135. Kochi, India: IEEE ACM, Kochi, India 2011.
49. P. Jaffe, J. Hodkin, and F. Harrington, "Develop- ment of a sandwich module prototype for space solar power," ser. IEEE Aerospace Conference, vol. 202, no. 10.1109/AERO.2012.6187077. Big Sky, Mon- tana: IEEE, March 2012, pp. 767–9166.
50. L. S. Mason, "A comparison of Brayton and Stirling space nuclear power systems for power levels from 1 kilowatt to 10 megawatts," in American Institute of Physics Conference Series, ser. American Institute of Physics Conference Series, M. S. El-Genk, Ed., vol. 552, Feb. 2001, pp. 1017–1022.
51. J. P. Penn and G. W. Law, "The aerospace corpora- tion systems studies and analysis of the space solar power (ssp) exploratory research and technologies (sert) concepts and applications," The Aerospace Corporation, Tech. Rep. ATR-01(7710)-1, 2000.
52. J. Mankins, N. Kaya, and M. Vasile, "Sps-alpha: The first practical solar power satellite via arbitrarily large phased array (a 2011-2012 nasa niac project)," in 10th International Energy Conversion Engineer- ing Conference, 2012.
53. N. Komerath, B. Dessanti, and S. Shah, "A gigawatt- level solar power satellite using intensified efficient conversion architecture," in Proceedings of the IEEE Aerospace

Conference,, ser. Paper 1548, no. DOI 10.1109/AERO.2012.6187079. Big Sky, Montana: IEEE, March 2012.

54. J. Bayard and T. Thomason. (2013, May) Cielo, runway-based space launch system aero-dynamics. EXTROVERT. [Online]. Available: http://www.adl.gatech.edu/extrovert/ace/

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55. J. Sandler and M. Lieberbaum. (2013, May) Fahlls, frequent access heavy lift launch sytem. EXTRO- VERT.
56. A. Guy and C. Swearingen. (2013, April) Runway-based launch system aero- dynamics. EXTROVERT. [Online]. Available: http://www.adl.gatech.edu/extrovert/ace/
57. W. Reese and W. Keller. (2013, May) A proposal for runway-based lifting body space access. EXTROVERT. [Online]. Available: http://www.adl.gatech.edu/extrovert/ace/
58. S. Chait and B. Kubica. (2013, May) X-57 condor: Runway-based space launch system aerodynamics. EXTROVERT. [Online]. Available: http://www.adl.gatech.edu/extrovert/ace/
59. E. Choi, A. Cerfon, M. Shapiro, J. Sirigiri, and R. Temkin, "Experimental study on gyrotron effi- ciency enhancement," in Vacuum Electronics Con- ference. IVEC'07. IEEE International, 2007, pp. 1–2.
60. A. Cavallo, J. Doane, and R. Cutler, "Low-loss broadband multimode corrugated waveguide perfor- mance," Review of scientific instruments, vol. 61, no. 9, pp. 2396–2400, 1990.
61. R. Olstad, "Straight corrugated waveguides," Gen- eral Atomics Energy Group Fusion Products, Tech. Rep., October 2011.
62. P. Managers, "System requirements review (srr): Misse-x srr presentation edited for space station nra as reference material only," NASA, June 2012.
63. R. Appleby, "Standoff detection of weapons and contraband in the 100ghz to 1thz region," IEEE Transactions On Antennas And Propagation, vol. 55, no. 11, pp. 2944–2956, November 2007.
64. T. Crowe, W. Bishop, D. Porterfield, J. Hesler, R. Weikle et al., "Opening the terahertz window with integrated diode circuits," Solid-State Circuits, IEEE Journal of, vol. 40, no. 10, pp. 2104–2110, 2005.
65. J. Booske, "Plasma physics and related challenges of millimeter-wave-to-terahertz and high power mi- crowave generation," Physics of plasmas, vol. 15, p. 055502, 2008.
66. K. L. Felch, B. G. Danly, H. R. Jory, K. E. Kreischer, W. Lawson, B. Levush, and R. J. Temkin, "Charac- teristics and applications of fast-wave gyrodevices," Proceedings of the IEEE, vol. 87, no. 5, pp. 752–781, 1999.
67. K. Felch, M. Blank, P. Borchard, P. Cahalan, S. Cauffman, and H. Jory, "Recent test results on a 95 ghz, 2 mw gyrotron," in Infrared, Millimeter and Terahertz Waves, 2008. IRMMW-THz 2008. 33rd In- ternational Conference on. IEEE, 2008, pp. 1–2. S.-T. Han, R.
68. G. Griffin, K.-N. Hu, C.-G. Joo, C. D. Joye, I. Mastovsky, M. A. Shapiro, J. R. Sirigiri, R. J. Temkin, A. C. Torrezan et al., "Continuous- wave submillimeter-wave gyrotrons," in Optics East 2006. International Society for Optics and Photon- ics, 2006, pp. 63 730C–63 730C.

69. M. K. Hornstein, V. S. Bajaj, R. G. Griffin, K. E. Kreischer, I. Mastovsky, M. A. Shapiro, J. R. Siri- giri, and R. J. Temkin, “Second harmonic operation at 460 ghz and broadband continuous frequency tun- ing of a gyrotron oscillator,” Electron Devices, IEEE Transactions on, vol. 52, no. 5, pp. 798–807, 2005.
70. A. C. Torrezan, S.-T. Han, I. Mastovsky, M. A. Shapiro, J. R. Sirigiri, R. J. Temkin, A. B. Barnes, and R. G. Griffin, “Continuous-wave operation of a frequency-tunable 460-ghz second-harmonic gy- rotron for enhanced nuclear magnetic resonance,” Plasma Science, IEEE Transactions on, vol. 38, no. 6, pp. 1150–1159, 2010.
71. R. McMillan, “Terahertz imaging, millimeter-wave radar.” in Advances in Sensing With Security Appli- cations, J. Bymes, Ed., 2006, pp. 243–268.
72. M. Kartikeyan, E. Borie, and M. Thumm, Gyrotrons: High power microwave and millimeter wave tech- nology. Springer Verlag, 2004.
73. G. Nusinovich, Introduction to the Physics of Gy- rotrons. Johns Hopkins Univ Pr, 2004.
74. E. Schamiloglu, “High power microwave sources and applications,” in Microwave Symposium Digest, 2004 IEEE MTT-S International, vol. 2. IEEE, 2004, pp. 1001–1004.
75. V. Filip, D. Nicolaescu, C. Plavitu, and F. Okuyama, “Analysis of microwave generation by field emitted electrons moving in crossed electric and magnetic fields,” Applied surface science, vol. 111, pp. 185– 193, 1997.
76. E. Egorov, Y. Kalinin, A. Koronovski, A. Hramov, and M. Morozov, “Microwave generation power in a nonrelativistic electron beam with virtual cathode in a retarding electric field,” Technical physics letters, Copyright c 2013 Narayanan Komerath Springer, vol. 32, no. 5, pp. 402–405, 2006.
77. A. Roy, J. Mondal, R. Menon, S. Mitra, D. Ku- mar, A. Sharma, and K. Mittal, “High power mi- crowave generation from coaxial virtual cathode os- cillator,” in Proceedings of the Asian Particle Ac- celerator Conference, Indore, India, 2007, pp. 523– 525.
78. I. Salama, C. Middleton, N. Quick, G. Boreman, and A. Kar, “Laser-metallized silicon carbide schot- tky diodes for millimeter wave detection and fre- quecny mixing,” in State-of-the-Art Program on Compound Semiconductors XXXIX and Nitride and Wide Bandgap Semiconductors for Sensors, Photon- ics and Electronics IV: proceedings of the interna- tional symposia, vol. 2003. The Electrochemical Society, 2003, p. 270.
79. V. Ilchenko, A. Matsko, A. Savchenkov, and L. Maleki, “High efficiency microwave and mil- limeter wave electro-optical modulation with whispering-gallery resonators,” SPIE, 2000.
80. L. Johansson and A. Seeds, “Generation and trans- mission of millimeter-wave data-modulated optical signals using an optical injection phase-lock loop,” Lightwave Technology, Journal of, vol. 21, no. 2, pp. 511–520, 2003.
81. S. Voingescu, “Mm-wave in cmos – opportunities above 50 ghz?” in CMOS Emerging Technologies Workshop, Banff, Canada, July 2006.
82. D. Wake, C. Lima, and P. Davies, “Optical genera- tion of millimeter-wave signals for fiber-radio sys- tems using a dual-mode dfb semiconductor laser,” Microwave Theory and Techniques, IEEE Transac- tions on, vol. 43, no. 9, pp. 2270–2276, 1995.
83. B. Razavi, “A millimeter-wave circuit technique,” IEEE Journal Of Solid-State Circuits, vol. 43, no. 9, pp. 2090–2098, September 2008.
84. R. Miyamoto, K. Leong, S. Jeon, and Y. Wang, “Dig- ital wireless sensor server using an adaptive smart- antenna/retrodirective array,” EEE Transactions On Vehicular Technology, vol. 52, no. 5, pp. 1181–1188, September 2003.

85. A. Verhoeven, W. Bongers, V. Bratman, M. Caplan, G. Denisov, C. Geer, P. Manintveld, A. Poelman, J. Pluygers, M. Shmelyov et al., “First microwave generation in the fom free-electron maser,” Plasma physics and controlled fusion, vol. 40, p. A139, 1998.
86. M. Oodo, R. Miura, and Y. Hase, “Onboard dbf an- tenna for stratospheric platform,” in Proceedings of the IEEE International Conference on Phased Ar- ray Systems and Technology, 2000, Dana Point, CA, USA, May 2000.
87. D. Goswami, S. Vijayaraghavan, S. Lu, and G. Tamm, “New and emerging developments in solar energy,” Solar Energy, vol. 76, pp. 33–43, 2004.
88. Y. Wang, K. Kempa, B. Kimball, J. Carlson, G. Ben- ham, W. Li, T. Kempa, J. Rybczynski, A. Herczyn- ski, and Z. Ren, “Receiving and transmitting light- like radio waves: Antenna effect in arrays of aligned carbon nanotubes,” Applied physics letters, vol. 85, no. 13, pp. 2607–2609, 2004.
89. A. Pham, J. Laskar, V. Krishnamurthy, H. Cole, and T. Sitnik-Nieters, “Ultra low loss millimeter wave multichip module interconnects,” IEEE Trans- actions on Components, Packaging, and Manufac- turing Technology, Part B: Advanced Packaging, vol. 21, no. 3, August 1998.
90. S. Nicolson, K. Tang, K. Yau, P. Chevalier, B. Sautreuil, S. Voinigescu, and E. Rogers, “A low- voltage 77-ghz automotive radar chipset,” IEEE 1- 4244-0688-9/07, pp. 487–490, September 2007.
91. E. Brookner, “Phased array radars-past, present and future,” in RADAR 2002. IEEE, 2002, pp. 104–113. V. Raghunathan, A. Kansal,
92. J. Hsu, J. Friedman, and M. Srivastava, “Design considerations for solar energy harvesting wireless embedded systems,” in Information Processing in Sensor Networks, 2005. IPSN 2005. Fourth International Symposium on. IEEE, 2005, pp. 457–462.
93. R. Corkish, M. Green, and T. Puzzer, “Solar energy collection by antennas,” Solar energy, vol. 73, no. 6, pp. 395–401, 2002.
94. R. Corkish, M. Green, T. Puzzer, and T. Humphrey, “Efficiency of antenna solar collection,” in Photo- voltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on, vol. 3. IEEE, 2003, pp. 2682– 2685.
95. A. De Vos, Endoreversible thermodynamics of solar energy conversion. New York, NY (United States); Oxford University Press, 1992.
96. B. Berland, L. Simpson, G. Nuebel, T. Collins, and B. Lanning, “Optical rectenna for direct conversion Copyright c 2013 Narayanan Komerath of sunlight to electricity,” Physics Review, pp. 323– 324, 2003.
97. H. Ries, “Complete and reversible absorption of radiation,” Applied Physics B: Lasers and Optics, vol. 32, no. 3, pp. 153–156, 1983.
98. S. Wright, D. Scott, J. Haddow, and M. Rosen, “The upper limit to solar energy conversion,” in En- ergy Conversion Engineering Conference and Ex- hibit,2000.(IECEC)35thIntersociety,vol.1. IEEE, 2000, pp. 384–392.
99. M. Green, Third generation photovoltaics: ad- vanced solar energy conversion. Springer Verlag, 2003.
100. B. S. Richards and A. Shalav, “Photovoltaics de- vices,” in The Handbook of Photonics 2nd Edition, M. Gupta and J. Ballato, Eds. CRC Press, Boca Raton, Florida, 2007, ch. 8, pp. 8–19.

101. T. Du Bosq, R. Peale, and G. Boreman, “Tera- hertz/millimeter wave characterizations of soils for mine detection: Transmission and scattering,” Inter- national Journal of Infrared and Millimeter Waves, vol. 29, pp. 769–781, 2008.
102. V. Sharma, “Effect of certain climatic factors over microwave propagation,” Journal of the Institution of Electronics and Telecommunication Engineers, vol. 20, pp. 114–118, 1974.
103. P. Dalela, M. Prasad, and A. Mohan, “A new method of realistic gsm network planning for rural indian terrains,” IJCSNS International Journal of Computer Science and Network Security, vol. 8, no. 8, pp. 362– 371, August 2008.
104. A. Chakraborty, “Fault tolerant fail safe system for railway signalling,” in WCECS 2009 Proceedings of the World Congress on Engineering and Computer Science, vol. II, San Francisco, USA, October 2009, pp. 1177–1183.
105. R. Ramos and A. Seeds, “Fast heterodyne optical phaselock loop using double quantum well laser diodes,” Electronics Letters, vol. 28, no. 1, pp. 82– 83, January 1992.
106. v L. Reddy and B. Reddy, “Some observations on the influence of hydrometeors on line-of-sight mi- crowave propagation at 7 ghz in tropics,” in Proceed- ings of ISAP’92, Sapporo, Japan, 1992, pp. 889–892.
107. G. W. Petty, A First Course In Atmospheric Radia- tion, 2nd ed. Madison, Wisconsin: Sundog Publishing, 2006, no. p. 283. H. Liebe and G. Hufford, “Modeling millimeter wave propagation effects in the atmosphere,” North Atlantic Treaty Organization, AGARD Report 454, 1989.