FIVE-NATION WIRELESS POWER TRANSMISSION DEMONSTRATION EXPERIMENTS

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1 Abstract

A roadmap is presented towards Space Solar Power, emphasizing international collaboration, synergy with the terrestrial energy industry, and with retail power beaming markets. The initial risk-reducing startup process includes two multinational experiments. The first will use the International Space Station to conduct a long-term experiment on millimeter wave power beaming, aiming, reception and atmospheric propagation. In a following experiment, two multinational satellites will be used to study and demonstrate a day-night power exchange between stations on opposite sides of the planet. Various aspects of these experiments are discussed.

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2 Nomenclature

GEO	Geo-Stationary Earth Orbit
Girasol	SSP converter satellite
GWe	GigaWatts of electric power
c	Launch cost to LEO, in $ per kg of payload
k	Viability Parameter for SSP architectures
kW	kiloWatts. One thousand Watts
kWh	kiloWatt-hours.
LEO	Low Earth Orbit
Mirasol	Ultralight solar collector satellite
MW	MegaWatts. One million Watts
NPV	Net Present Value
P	Price of electric power, US dollars per kWh
PV	Photovoltaic
ROI	Return on Investment
S	Specific Power, kW to Earth per kg in orbit
SSP	Space Solar Power
SPG	Space Power Grid
TWe	TeraWatts of electric power. One thousand GWe
η	Efficiency of transmission to Earth

3 Introduction

When Space-based solar power [1–3] 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, 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, much more than with today's communications satellites and the Global Positioning System (GPS). The massive global investment needed for this enterprise, requires a commercially viable, revenue-generating progression. Significant advances will occur before this becomes a reality. The risks, superstitions and other obstacles will have been systematically confronted, overcome or circumvented. Numerous architecture options have been proposed, [4–18]. These offer many ideas that will be parts of the eventual solution framework. One roadmap, developed through several years of refinement and exploration, is summarized. The first steps are logically derived.

Two sequential steps are proposed in this paper. The first is an experiment using the International Space Station (ISS), partly derived from Potter *et al* [18]. From the ISS, a small amount of solar-generated electric power will be beamed to participating nations over a period of a few years. This experiment will collect data and improve technology on the choice of frequency, atmospheric beam propagation, magnetic field effects, health hazards, pointing uncertainty and not least, the intricacies of several nations working together on a truly global project.

The second 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 [19, 20].

Other technical advancements needed for full scale SSP are summarized below. Many of these can be accomplished in ground experiments and modeling during the course of the proposed 5-nation project, and will set the stage for a rapid progression to realizing the dream of Space Solar Power.

3.1 Organization of the paper

The paper is organized as follows.

1. The Viability Parameter for SSP [21, 22], shows why it is essential to achieve certain levels of specific power, efficiency, launch cost and selling price of power. We then discuss why and how SSP can become viable.
2. The technical advances needed, and their uncertainties, are logically reduced to the two proposed demonstrations.
3. The ISS experiment is summarized.
4. The multinational power exchange is introduced.
5. These open a discussion on the steps needed to proceed

towards the two experiments.

4 Under What Conditions Will SSP Become Viable?

Much has been written and proposed about SSP, a long-time dream of humanity [4, 10, 23–31]. It has not been realized because we have not achieved the technical and economic state of progress to build a viable system. A rule of thumb for viability of SSP developed from architecture studies by our group is the value of the parameter k which was first introduced in [32]. The value of 25000 in Equation 1 is set such that k∼1 is where the architecture is reasonably certain to achieve viability, i.e., reach zero Net Present Value and the desired size, at an acceptable Return on Investment, by Year 50 from project start.

$$k = 25000 P \eta s / c \tag{1}$$

Here P is the selling price of space-generated power in \$/KWh, η is the efficiency of transmission to the ground, S (kWe/kg) is the specific power, defined as the power delivered to the terrestrial grid per unit mass needed in orbit to do so and C (\$/kg) is the launch cost to low earth orbit (LEO). Today the launch cost is not below \$2200 per kg to LEO, and most people would say \$5000 per kg. The photovoltaic (PV)-based, GEO-located SSP architectures that have been proposed to-date do not promise values of k over 0.3, and thus have little hope of becoming commercially viable on a large scale. Unsurprisingly, most proposals to-date do not project beyond the first small-scale, taxpayer-funded demonstration.

Our architecture focuses on the innovations needed to improve the specific power and end-to-end efficiency parameters. GEO-based microwave architectures [33–35] rarely get beyond 0.2 kW per kg in orbit. PV architectures even with our SPG architectures using mid Earth orbit trajectories and millimeter wave beaming, can barely break through 1.0.

In prior work we have presented two major departures from traditional architectures:

1. Reduce the orbit height from 36,000 km (GEO) to 2,000 km [36]. This of course implies dynamic pointing and beaming, with power exchange intervals as short as a few minutes over any given station for each satellite. As mentioned at the outset, when SSP becomes significant, there will be thousands of satellites in orbit, so continuous beaming, even though it is not essential, will be quite easy to ensure.
2. Increase the beaming frequency from the 2.4 and 5.8 GHz microwave range, to 220 GHz millimeter waves [37]. This is a substantial technical risk, but we project that with present research advances in milimeter waves [38–41] and SSP as motivator, the conversion efficiency and mass-specific power will reach levels that make this viable within the time available before the first SSP converter satellite design is frozen for construction and deployment, i.e., the next decade.

The effect of these two changes on infrastructure size can be seen from Equation 2, the well-known Friis antenna equation relating transmitter and receiver diameters (D_t, D_r), wavelength λ and beaming distance R, and from Table 1. The ISS and 2000km orbits shown in the table are dynamic beaming examples, so that the receiver is sized to capture beams at 45 degrees inclination from the zenith. The factor of 6.48 instead of the usual 2.44 is because [42] utility power systems will insist on receivers that capture at least 93.8 percent of the beam energy (second bright ring of the Airy Disc [43, 44] formed by the diffraction pattern of a finite-aperture, high gain, Gaussian beam), rather than the 84 percent main-lobe capture used in presentations of GEO / microwave architectures.

$$D_r = \frac{6.48 R \lambda}{D_t} \tag{2}$$

Three other advances boost the Viability Parameter [45].

1. Use tethered and high-altitude, lighter-than-air atmospheric platforms [46–48] to carry antennae [49]. Millimeter waveguides in the tethers eliminate the high losses of transit through the wet and dense lower atmosphere.
2. Alleviate the intermittency and improve the business case of terrestrial renewable power generation, using a synergistic Space Power Grid for power exchange. This will be the initial mechanism to fund risk-reduction and market establishment, before launching the massive SSP satellites [20, 32]. This point is most difficult to convey to SSP enthusiasts. But opening this

Orbit	GHz	Dt, m	Dr, m
ISS	220	2.26	2215
2000km	220	50	500
GEO	220	50	6362
GEO	5.8	50	241324
GEO	2.4	1000	29160

TABLE 1. Receiver Sizes for Some Altitudes and Frequencies

global public-private collaboration early is essential to bring about Space Solar Power as a global power solution.

3. Use Brayton cycle conversion from intensified sunlight, rather than photovoltaic conversion. The mass per unit power for PV conversion remains constant, independent of the power or intensity level. Beyond about 2 suns of intensity, PV conversion offers no mass reduction because of the need for an active thermal control system [50]. On the other hand, the mass of Brayton cycle engines scales favorably with increasing power level [42, 51].

The various elements of this architecture are illustrated in Figures 1 and 2. The rationale and basis for each of these are explained in [45] referring to the progression of the Space Power Grid architecture over the past 6 years. The roadmap laid out in that paper shows that full replacement of terrestrial fossil power generation with SSP can be achieved within 31 years from project start, taking into account realistic consideration of the time needed to build the massive infrastructure needed both for the satellites and for the launch facilities and vehicles to deliver and maintain them in orbit. In Table 2 from [45] the mass budget for the Space-based infrastructure needed to deliver 1 GWe at Earth using this Space Power Grid architecture is compared to those of other recent proposed architectures for SunSats, namely the HALO architecture studied by the Aerospace Corporation [52] and the recent SPS Alpha architecture [53], both based in GEO and using microwave beams at 5.8GHz or lower frequencies. The infrastructure size comes down by a huge factor. Not all of this maps proportionately to mass and cost reduction, because 220 GHz technology may be relatively expensive, and the space

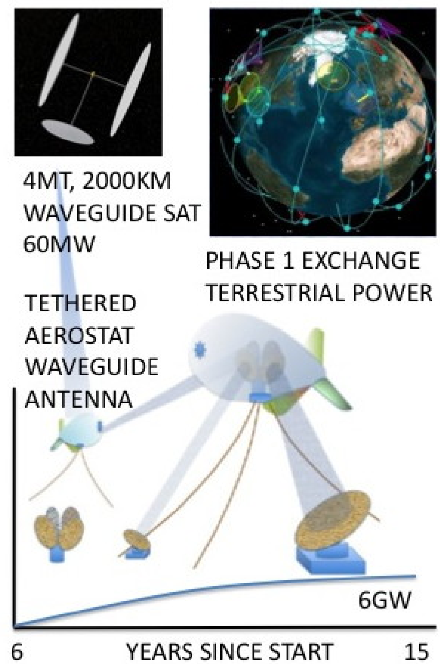

FIGURE 1. In Phase 1, a 2000 km constellation of 100 waveguide satellites of 4000kg each is built over 9 years, transacting 60MW power each, between terrestrial power plants and customers. Waveguides inside aerostat tethers minimize atmospheric losses.

antennae in that regime may have a higher mass per unit area. However, there is indeed a gain of an order of magnitude, and that brings the viability factor sufficiently above 1.0. In addition, our Intensified, efficient Conversion) Architecture (IηCA) uses a Brayton cycle to convert high-intensity solar energy to mechanical work and then to millimeter wave beamed power. This promises specific power over 1.6 kW per kg [54]. The technical parameters needed to make IηCA a reality (high temperature materials) are within reach, and therefore, so is full-scale Space Solar Power. However, the large satellites cannot be launched today. The technologies need development. So our plan is to start on a roadmap that systematically removes the uncertainties and market risks while giving the technology the needed time and urgency to develop.

FIGURE 2. In Phase 2, a 2GW ultralight Mirasol sunlight collector and a 1GW, 220GHz Girasol Brayton cycle converter, in orbits near 2000 km, form the standard component of a Space Solar Power constellation, growing to over 4 TeraWatts of SSP by Year 40. The Earth link system is expanded from Phase 1 with minimal technical risk.

Item	Mirasol Concept	Halo Concept	SPS-Alpha Concept
Optical Elements	6000 optical elements	100 orbiting reflectors	∼5000 reflectors
Energy Conversion	Solar Thermal	PV Array	PV Array
Power Generation	Mill Wave Generator	Solid State Amplifiers	∼200,000 Modules
Beam Frequency	220GHz (Mill Wave)	5.8 GHz (Microwave)	2.45 GHz (Microwave)
Power Level	1 GW	1.2GW	2 GW
System Mass	677MT	13,044MT	∼9,350MT

TABLE 2. Comparison with Halo and SPS-Alpha Concepts. From [45].

5 Primary Technical Advances and Uncertainties

1. Even with a specific power of 1kW per kg placed in orbit, reaching 4TW within 50 years, with the first 10 years needed for development, means placing 4 billion kg in orbit in 40 years. Given a heavy lift payload of 100 tons per launch, this works out to 1000 launches and recoveries per year, or one every working day from each of 4 sites around the world for 40 years. Only a runway-based, airbreathing launch and recovery architecture can offer enough operational productivity. Recently, several student projects have considered this problem and their efforts can be seen at [55–59]. With this, we project that the cost can be reduced below \$1300 per kilogram to LEO, and perhaps much lower.

2. Present gyratron technology [60], shows over 50% conversion efficiency, and specific power above 2.5 kW per kg for just the millimeter wave converter, at power levels on the order of 1MW. Recent discussions with US aerospace companies indicate that conversion efficiency exceeds 90 percent at the single chip level for large-array solid state approaches.
3. Transiting the moist and weather-prone lower atmosphere with 220GHz beams, can be done using waveguides tethering aerostats at altitudes of 4000 m or higher. Transmission between these altitudes and Space is essentially loss-free (better than 90% even at 2800 m, per astronomical observatory data). Horizontal transmission between aerostats is an option, albeit limited in distance by the Earth's curvature. This offers a quick option to bring an electric power grid to rural areas that are at present off the terrestrial grid. The waveguides [61, 62] exhibit very high power-carrying capacity, on the order of 100 MW through a 63mm diameter corrugated "slow mode" waveguide.
4. The interaction of high-power millimeter wave beams with the atmosphere remains uncertain (at least in the open literature). Options such as tunneling through the lower atmosphere using the first few seconds of 60 MW beaming, remain to be explored.
5. Little is known about the safety of 220 GHz radiation, nor about the level of spillage and scattering when such beams transmit the atmosphere. The aerostat-

based system ensures that well over 90% is captured into waveguides and never interacts with free air below 4000 m altitude. However, the public must be reassured about the failsafe systems.

6. The cost of millimeter wave converters is quite uncertain. Research on automobile radar provides a mass market impetus that may solve several of the technical issues and production logistics, and again, the sheer size of the demand from the Space Power Grid architecture should generate enough competition to bring down prices.

5.1 Summary Recommendation: Millimeter Wave Beaming ExperimentsTo Jump-Start SSP

From the above, we conclude that the first need is for a public demonstration of low-level power beaming between Space and the surface, around the world, running long enough to ensure confidence that all probable atmospheric events are encountered. This would be complemented by ground experiments, increasing in beam power and studying the interaction of the beam with the atmosphere at high levels. Technologies such as the waveguide-tethered aerostat antennae will be demonstrated. Power exchange experiments between nations across the world, led by a multinational satellite fleet of 4 to 6 satellites, will set the stage for the first 100 Waveguide satellites of a Space Power Grid, along with the first 200 ground stations. Other ground and space experiments would demonstrate intensifying solar power, building helium Brayton Cycle solar converters, low-mass electrical generators, and millimeter wave converters. These would lead to the first Gigawatt level system towards full-scale SSP. Thus, the ISS experiment is the logical first step.

6 The Proposed 5-Nation ISS Millimeter-wave Beaming Experiment (IMBE)

This proposal is partly adapted from one presented at the ISDC in 2011 by Potter *et al* [18]. They envisaged two 10-KW generators on the ISS. The first was at 5.8 GHz, and the other at 94 GHz using a solid-state converter. Given the small transmitting apertures, large receivers such as the Goldstone Observatory antenna in Arizona and a Florida site were chosen as examples. The 5.8 GHz beam was expected to yield less than 100 watts at either location. The 94 GHz beam was expected to yield 7kW at Goldstone, and roughly 4kW at the humid Florida site.

6.1 Objectives

The objectives of the 5-nation ISS experiment are:

1. Demonstrate safe 220GHz beaming from the ISS.
2. Measure pointing error worldwide, year-round.
3. Measure beam spread at 220 GHz to locations worldwide.
4. Correlate beam attenuation with meteorological data.
5. Set up a template for international SSP collaboration.

The items at launch will be packed into two Express Logistics Carrier ELC modules and another package that consists of the flat transmitter array, waveguides and structural elements. The electronics package in each ELC consists of the 220 GHz signal generator, DC-220 GHz power amplifier, power controller and safety system, and the active thermal control system with radiator needed to dissipate as much as 500 watts. A solid-state amplifier is preferable to a gyrotron, but may be cost-prohibitive in the initial system. In that case, a solid-state generator system packed in an ELC may be shipped on a later flight, to exchange with the gyrotron-based package. The transmitter will be a solid state phase array. Waveguides tuned to 220GHz will be used to convey the power from the amplifier to the transmitter. Once at the ISS, the transmitter array and waveguides will be deployed and attached to the US Truss at nadir points P3 or S3, and connected to the ELCs, using the ISS remote manipulator. The ELCs will each be plugged into one of the external power outlets, which are rated at 500 to 750 watts each at 28VDC. Thus the power beaming experiment in this case will start with 1 kW of DC power. With a gyrotron converter, only about 100 watts may be beamed, with as much as 63 watts arriving after conversion to DC or AC at the ground. With a solid state generator, as much as 720 watts may arrive as DC or AC at the ground. Thus the initial ELC with the gyrotron package may have an active thermal control system to radiate out all of the 500 watts each, while the later version carrying a solid state converter will only be required to dissipate less than 100 watts each.

Figure 3 visualizes the beaming experiment. The phase-array transmitter shaped as a square plate will be able to sweep a beam 45 degrees forward and aft, and 10 degrees to the sides as shown in Figure 4, to link with ground stations under the ISS. At present we anticipate that the ELC and transmitter array will be attached at the nadir of the S-3 or P-3 truss locations. Attachment of the waveguide and the transmitter will have to be done by robotic manipulator operations. No need for human extravehicular activity is anticipated. Onboard monitoring is expected to be limited to essential safety monitoring and resets after safety shutoff events. All other command, control, data acquisition, telemetry and storage are expected to be conducted from ground stations and ISS mission control stations.

6.2 Ground Infrastructure

A typical ground receiver is conceptualized roughly in Figure 5. At the initial stages the receivers will be on the ground. As the experiment progresses the ground stations will deploy waveguide-aerostat receivers for testing. It is noted here that for the ISS beaming experiment, the transmitter in Space is limited to a 2m x 2m plate by ISS constraints (a larger antenna may win approval but require more sophisticated packaging and deployment). Thus, from Table 1, the ground antenna size is quite large, and not suitable for beam capture using aerostats. The aerostat testing in this phase will be simply to validate predictions and refine the system. Proceeding to the 6-satellite multinational power exchange experiment discussed later, transmission and reception at the ground station could be accomplished using transmitters distributed over a formation of aerostats, for the 5000-kilometer orbit altitudes. For the Phase 1 Space Power Grid, with 50-meter antennae on the waveguide satellites in 2000 km orbits, the ground antennae can again be accommodated on a formation of aerostats, or using large stratospheric platforms beaming to and from smaller tethered tropospheric aerostats. The point here is that the ISS beaming experiment provides the opportunity to refine all these technologies before deploying the production system.

7 ISS Experiment Process

The IMBE is analogous to the MISSE-X or Materials International Space Station Experiment [63]. The MISSE-X holds a rectangular plate below the ISS from Truss station S-3, facing forward. Material samples attached to the plate experience the radiation field for a specified time, after which they are removed and replaced with new samples. The launch, attachment and deployment phases are quite similar to IMBE, and the mass is also similar. We will use the development process of the MISSE-X, published on the Internet, for guidance. Figure 4 shows the operational concept of the IMBE. The experiment package can be accommodated as unpressurized cargo, and will fit as one of 3 cargo containers taken up in the Space-X Dragon launch vehicle. Once at the ISS, the preferred attachment location is at site 3 on the nadir side of the starboard or port truss

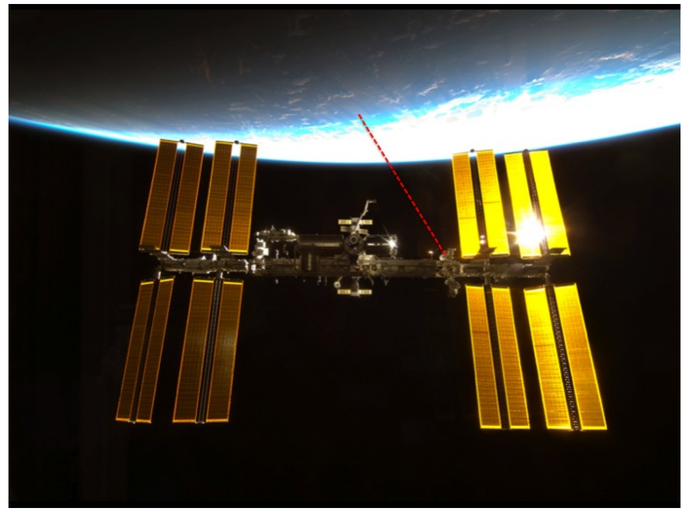

FIGURE 3. Schematic depiction of beaming from the ISS to ground receivers.

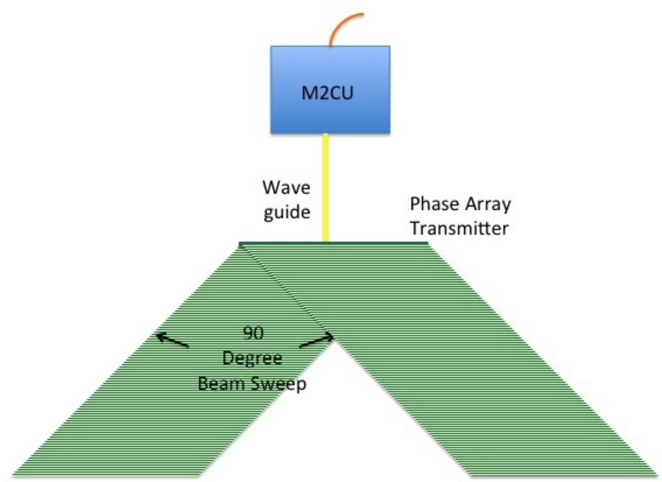

FIGURE 4. The phase array transmitter will be able to sweep the beam 45 degrees fore and aft, and 10 degrees side to side.

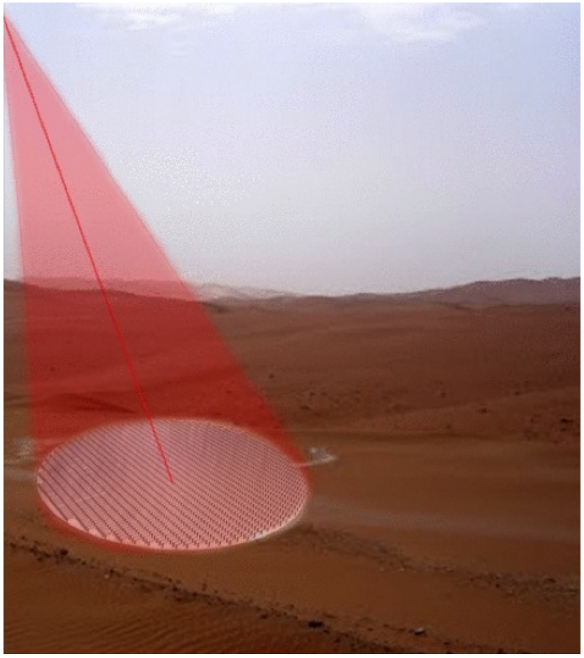

FIGURE 5. Conceptual sketch of a ground receiving station for the ISS beaming experiment. The failsafe link beam is indicated in the middle.

(S-3 or P-3). Rather than attach to a pallet, the experiment will be deployed with the power and control package inside an ELC attached to the truss. The transmitter antenna will be attached at the end of a 2 or 3 meter waveguide support. The experiment components are illustrated in Figure 6. Typical mounting of EXPRESS Logistics Carriers outside the ISS are shown in Figure 7.

7.1 TRL and Hardware Development

Many of the experiment components can be implemented with mature Commercial Off The Shelf (COTS) components. The millimeter wave converter system will be specially developed for the ISS experiment, to minimize mass. The waveguide will be adapted from standard components used in the nuclear industry [62]. The phase array transmitter will be specially built for the ISS experiment. The areas of high risk are the millimeter wave converter, the transmitter antenna, and its beam pointing and sweeping capabilities.

7.2 ISS Facility Requirements

The requirements are:

1. The equipment shall be delivered using a spacecraft with capabilities at the level of a SpaceX Dragon vehicle.
2. The equipment shall be retrieved from the delivery vehicle, unpacked and attached to the ISS using manipulators.
3. The ISS shall provide 1000 W of DC power input and at least 100W continuous wave (cw) output at 220 GHz.
4. The beam shall achieve a pointing accuracy of less than 10 meters mean circular error, within 10 orbits around Earth, while performing adaptive corrections.
5. A low-power laser link beam shall be activated along the same path as the main power beam, before the power beam is activated. In case of link error, the beaming shall be stopped within 1 millisecond and not re-activated until the link error is satisfactorily investigated and corrected.
6. The beam shall point upto 45 degrees forward, and sweep steadily to 45 degrees aft, or 10 degrees to port or starboard.
7. There shall be unobstructed visibility from the transmitting phase-array antenna, within the regions specified above.
8. Continuous data exchange shall be operating immediately prior to, during and immediately following power transmission, between the ISS-based system and the ground receiver facility, at a rate sufficient to meet other stated requirements.

7.3 Power Budget

The initial plan is for 1 kW DC, accessed through two 500-watt ELC attachments. A conservative conversion efficiency of 10% would result in a 50-watt beam being transmitted through waveguide to the transmitting antenna. This is sufficient, when received at an antenna sized for 94% capture area, as can be done with 220 GHz. Actual efficiency figures are around 10 % with gyratron technology, and upto 90% with solid state technology. The former is essentially available off the shelf but must be ruggedized for space launch and installation. The latter must be scaled up in production from microchips to deliver the needed wattage. As the project wins greater support from NASA

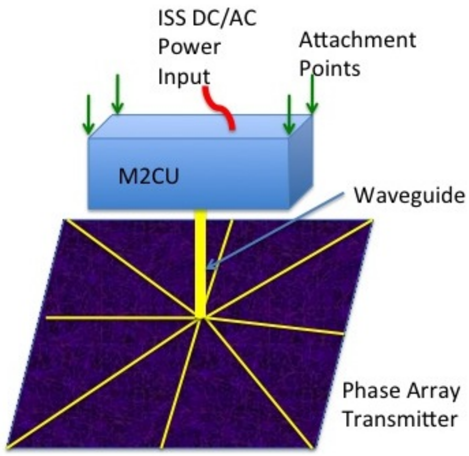

FIGURE 6. Experiment components schematic

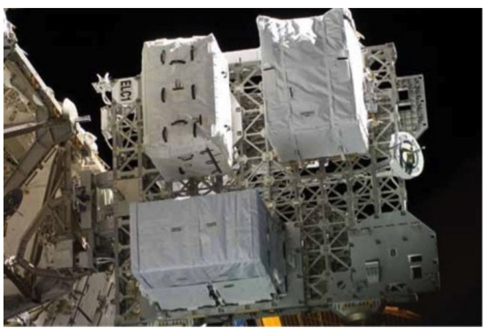

FIGURE 7. Typical mounting of ELCs at the ISS. From the NASA ISS Reference Manual, courtesy NASA

and other space agencies, we expect that Request for Information announcements will bring in proposals for larger systems with high efficiency. Given this, the first launch will probably be of a system with 1kW DC input, and over 500, perhaps 900 Watts of beamed power output at 220 GHz. The thermal control system is part of the standard ELC, and will be sized for 500W on each ELC on the initial packages.

7.4 Measurements and Data Processing

Data needs are listed below:

1. System health monitoring
2. Command and reprogramming
3. Communications with ground stations
4. Beam pointing, link establishment and disconnection
5. Test beam return processing

FIGURE 8. Tracks of different orbits of the ISS

6. Correlation with ISS weather and cloud imaging

7.5 Support Needs

Funded projects in the participating nations will be used to develop, build and test the millimeter wave conversion system, the data acquisition and analysis system, and the millimeter wave beaming equipment. Installation, deployment, and continigencies demanding removal/replacement, and eventual end-of-mission detachment and return, require ISS manipulator arm operations. A central control station must be manned continuously to monitor the experiment operation, safety and data collection, along with coordinating handoffs between ground facilities as needed. Each participating nation must provide their own ground facilities to receive and analyze the beamed power from the ISS.

7.6 Ground Station Selection

Ground tracks of the ISS are shown in Figure 8. Access time within a 45-degree cone varies with latitude as shown in Figure 9. The ground stations in Table 3 were chosen for example calculations in this paper.

7.7 Preliminary Hazard Analysis

The primary hazard identified to-date is that of excessive heat retention in the ELC due to failure of the thermal control system. One solution is to have redundant temperature sensors which will cut off electric power to the ELC if the temperature exceeds safe limits. The beam power is low enough to not pose any hazard to humans or animals if accidentally irradiated. The lock-in failsafe beam link is expected to eliminate any accidental exposure for over 1 mil-

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

TABLE 3. Example locations, with number of power links per year and mean link duration

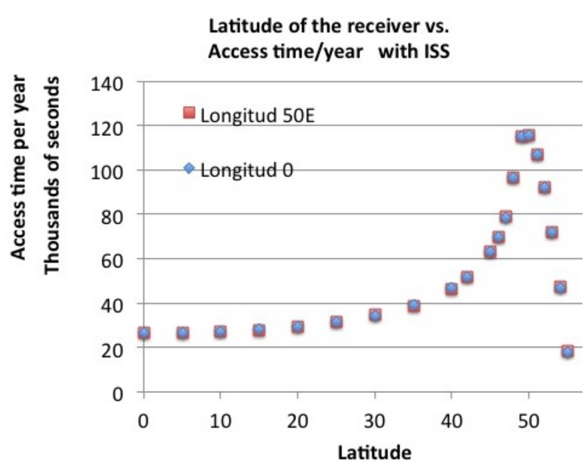

FIGURE 9. Variation of power beaming link time per year with latitude

lisecond. A second hazard being considered is that of aircraft or balloonists flying into the beam path. Airspace controls will have to be instituted over beaming locations until this issue is properly studied and understood; however, the low beam power is expected to cause no damage, injury or interference with control and communications. The beam trip will shut off in 1 millisecond.

8 The multinational power exchange experiment

The second experiment that we are proposing will launch 4 to 6 satellites into orbits at 5000 km. These satellites will act as waveguide relays, directing beams from one ground station to another, perhaps as far as the other side of the planet. In prior work [21] we showed that with 6 satellites we could do a 2-nation power transfer, while with just 4 would suffice with 4 we nations participating. This experiment will take power levels into the tens of Megawatts, and set the stage for the transition to Phase 1 of the Space Power Grid architecture.

9 Discussion on the steps needed to proceed towards the two experiments

What is the roadmap to proceed towards these two experiments?

1. Multinational team develops white paper
2. Presentation to space agencies.
3. Team develops planning document, space agency RFI.
4. System engineering plan detailed
5. Design reviews lead to construction and ground testing
6. Development of ground facilities
7. Launch and deployment
8. 6-month result review leads to next phase of experiment
9. Design reviews of Multinational experiment
10. Ground facility and satellite development
11. Power exchange experiment begins
12. 2-year reviewleads to Space Power Grid Phase 1 RFQ

10 State and prospects of millimeter wave technology

Millimeter wave technology poses the primary technical motivation for the ISS experiment. Reference [41] surveyed the available options and opportunities, and the following discussion is condensed from there. In the spectral range from 100 GHz to 1 THz, legacy methods from both the microwave and laser optics communities come into play, with interesting possibilities for integration. Millimeter waves are used in detecting weapons and contraband using various properties of the human skin, tissue, thermal characteristics of materials, emission spectra, and scattering characteristics of textiles [64]. Crowe [65] describes solid-state circuits that use nonlinear diodes to extend microwave technology through the millimeter wave regime into the THz regime. Booske [66] pointed out that solid-state devices generate low putput (100 mW) and offer no nonlinear scaling, thus requiring very large arrays to generate high power. Vacuum devices (gyratrons) today generate large amounts of power (1 MW) in the 200 to 460 GHz range [67–71], however, their efficiency is only on the order of 50 percent at best, and their specific output power (output power per unit mass of the equipment) is low [72–75]. The best-known number that we can quote is a 2MW aircraft-mounted millimeter wave system using a gyratron with a mass of 800 kg reported to have been conducted by the US company CPI, giving specific power of 2.5 kW/kg for the millimeter wave converter alone. Electro-optical techniques are beginning to come into play [76–78]. Direct conversion of sunlight to millimeter waves is a game-changing prospect, using wide bandgap materials (e.g., crystalline silicon carbide of bandgap 3.2 eV), and the connectivity of several p-n junctions in series using high electrically conductive material (e.g., graphene). Salama et al [79] fabricated a laser-metalized antenna-coupled Schottky diode for 94 GHz conversion. Ilchenko et al. [80] describe millimeter wave generation by resonance of a micro-spherical cavity. Whispering-gallery modes of a toroidal lithium niobate cavity electro-optic modulator superposed with a stripline resonator, showed resonance Quality (Q) factors projected to exceed 10 billion.

Optical approaches to millimeter wave generation, especially using phase-locked loops, appear to be an active area of research [81–84] awaiting mass-production markets. Tracking antenna technology has enabled a large number of self-aligning phase array receivers to simultaneously track and communicate with beaming transmitters [85]. Verhoeven et al [86] reported cw generation of over 750 kW, continuously tunable over the range from 130 GHz to 260 GHz, using an electron-beam MASER with over 50% overall efficiency.

Oodo [87] describes a digital beam-forming antenna for stratospheric airships in the 25 to 30 GHz range. Goswami [88] postulate 80-90% efficient direct conversion of solar energy using nanoscale antennae. Wang *et al.* [89] postulate that carbon nanotubes interact with light in the same manner as simple dipole radio antennae. CMOS process technologies enable low-cost, highly integrated 60 GHz and 77 GHz transceivers suitable for high-volume production [40, 90, 91]. Brookner [92] describes low-cost mass-produced 77 GHz phased arrays for automobiles.

At the power receiving station, the millimeter wave energy must be converted to electrical energy in either direct current or alternating current mode to suit end-user devices. Rectenna arrays have been described to convert beamed power to DC or AC for the end-user [93–97]. The Landsberg efficiency limit of 93.3% is reachable using a rectenna assembly concisting of nonreciprocal absorbers such as optical circulators [98–101].

11 Science Issues

What results might be anticipated from the ISS experiment? The first is an end to the uncertainty about millimeter wave transmission between Space and the ground, with the accumulation of a worldwide database. Interest in reception by aerostats and stratospheric platforms will drive research on the atmospheric attenuation as a function of altitude. Auxilliary issues will trigger substantial research, such as on the effects of millimeter waves on various materials [102]. Studies triggered by the use of microwave communications, for instance, [103–105] demonstrated the effects of refractive index, rain, humidity, and sea-breeze on the fadeout of microwave signals in the tropics. Even with at 7 GHz fog in river valley areas in a tropical climate causes signal outages [106, 107]. This should give pause to the belief that using microwave frequencies below 10 GHz guarantees high-efficiency, all-weather transmission.

11.1 Beam attenuation

Atmospheric transmission will encounter many issues and imperfections. Some have argued that the mirror flatness needed for perfect relays is too fine, and if that were achievable, astronomy would be much further advanced. This is spurious. It is a given that some form of correction will be needed. This is achievable by reflecting a low-power laser beam (the trigger beam) along the center of the main beam path, and analyzing the return to determine the transfer function. This transfer function is used to correct the transmitter. With a large phase array transmitter, adjusting the phase of individual elements to achieve a given beam profile and directionality is feasible, though it requires non-trivial, high speed signal processing. These considerations again drive the optimum solution towards large arrays of solid-state MMICs that offer the potential to integrate receiver, converter, transmitter, beam steering, frequency selection, and antenna phase correction possibilities.

Four types of attenuation are usually considered. The first is free-space spreading from an isotropic antenna, which is proportional to the square of distance. This is minimized down to the diffraction limit by focusing as tightly as possible. The second is spillover loss. Millimeter wave beaming allows design to capture up to 94 percent, as opposed to the 84 percent (primary lobe only) commonly used in SSP architectures using low-end microwaves. Absorption or scattering by gaseous nitrogen, oxygen, and water vapor, increase as altitude decreases. Placing the receivers on aerostats at 4000 meters brings a 27-deg. C drop in temperature and a large drop in pressure. The fourth is scattering by dust, ice, fog or rain particles. Data from [108, 109] show that above 4km, attenuation is essentially as low as in Space, with excellent windows at 94GHz, 140 GHz, 170 GHz and 220 GHz.

12 Conclusions

1. Space Solar Power is within reach.
2. The primary uncertainties are in the generation and beaming of millimeter wave power.
3. Two experiments are proposed, to reduce the risks and obtain necessary data and confidence with millimeter wave beaming.
4. The first is an experiment where a transmitting antenna placed under the International Space Station transmits power to ground stations located in several nations, collecting data on pointing accuracy, atmospheric conditions and their effects on the power beaming.
5. The second experiment will use 4 to 6 waveguide satellites stationed in 5000km-high orbits, to exchange beamed power between stations on the ground.
6. The technical status of millimeter wave beaming is ripe enough to warrant launching these experiment projects.

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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 Today*, 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 feasibility study, phase 1,” NASA contract, 1996.

[6] I. Bekey and R. Boudreault, “An economically viable 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 communications, 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 Astronautica*, vol. 59, no. 1, pp. 132–138, 2006.

[9] N. Nagatomo and K. Itoh, “An evolutionary satellite 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 countries,” *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

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. Niino, and M. Mori, "Development of solar-pumped lasers for space solar power station," in *INternational astronautical congress*, Fukuoka, Japan, October 2005.

[15] S. Sasaki, K. Tanaka, K. Higuchi, N. Okuizumi, S. Kawasaki, M. Shinohara, K. Senda, and K. Ishimura, "Feasibility study of tethered solar 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 transmission 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 Development 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*, M. E. Genk, Ed. American Institute of Physics, 2006.

[20] N. Komerath and N. Boechler, "The space power grid," in *Proceedings of IAC 2006*, no. IAC06-C3.4.6. International Astronautical Federation, September 2006.

[21] 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.

[22] 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.

[23] D. Criswell, "Lunar solar power system," *Potentials, IEEE*, vol. 15, no. 2, pp. 4–7, 1996.

[24] J. Mankins, "A fresh look at space solar power: New architectures, concepts and technologies," *Acta Astronautica*, vol. 41, no. 4, pp. 347–359, 1997.

[25] J. Mankins, C. Miller, T. Dinnerman, D. Cheng, R. Faith, C. Linhao, W. Leary, D. Brody, M. Mayfield, K. Cowing *et al.*, "The space solar power satellite," *Aerosp. Am*, vol. 35, pp. 30–36, 1997.

[26] G. Landis, "Reinventing the solar power satellite," NASA, report 2004-212743, 2004.

[27] 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 internationally?" *Solar Power Satellites*, pp. 67–78, 2012.

[30] N. Geuder, V. Quaschning, P. Viebahn, F. Steinsiek, J. Spies, and C. Hendriks, "Comparison of solar terrestrial 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 Information 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, "Parameter selection for a space power grid," in *Space 2008*, no. AIAA Paper 2008-7711, September 2008.

[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," *Electronics 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 Systems*, vol. 7, p. TBD, 2011.

[42] N. Komerath and B. Dessanti, "Brayton cycle conversion for space solar power," in *Proceedings of the 48th AIAA/ASME/SAE/ASEE Joint Propulsion Conference and Exhibit*, no. DOI: 10.2514/6.2012-4287. Atlanta, Georgia: AIAA, August 2012.

[43] M. Born, E. Wolf, and A. Bhatia, *Principles of optics*. Pergamon Pr., 1970.

[44] B. Dessanti, R. Zappulla, N. Picon, and N. Komerath, "Design of a millimeter waveguide 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 Conference, 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 Exhibit; 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 australia," MONASH UNIVERSITY EPRESS, 2008.

[48] C. Lambert, A. Saunders, C. Crawford, and M. Nahon, "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.

[49] N. Komerath, A. Kar, and R. Pant, "Antenna considerations 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.

[50] P. Jaffe, J. Hodkin, and F. Harrington, "Development of a sandwich module prototype for space solar power," ser. IEEE Aerospace Conference, vol. 202, no. 10.1109/AERO.2012.6187077. Big Sky, Montana: IEEE, March 2012, pp. 767–9166.

[51] 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.

[52] J. P. Penn and G. W. Law, "The aerospace corporation 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.

[53] 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 Engineering Conference*, 2012.

[54] 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.

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

[56] J. Sandler and M. Lieberbaum. (2013, May) Fahlls, frequent access heavy lift launch sytem. EXTROVERT.
[57] A. Guy and C. Swearingen. (2013, April) Runway-based launch system aerodynamics. EXTROVERT. [Online]. Available: http://www.adl.gatech.edu/extrovert/ace/
[58] 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/
[59] 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/
[60] E. Choi, A. Cerfon, M. Shapiro, J. Sirigiri, and R. Temkin, "Experimental study on gyrotron efficiency enhancement," in *Vacuum Electronics Conference. IVEC'07.* IEEE International, 2007, pp. 1–2.
[61] A. Cavallo, J. Doane, and R. Cutler, "Low-loss broadband multimode corrugated waveguide performance," *Review of scientific instruments*, vol. 61, no. 9, pp. 2396–2400, 1990.
[62] R. Olstad, "Straight corrugated waveguides," General Atomics Energy Group Fusion Products, Tech. Rep., October 2011.
[63] P. Managers, "System requirements review (srr): Misse-x srr presentation edited for space station nra as reference material only," NASA, June 2012.
[64] 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.
[65] 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.
[66] J. Booske, "Plasma physics and related challenges of millimeter-wave-to-terahertz and high power microwave generation," *Physics of plasmas*, vol. 15, p. 055502, 2008.
[67] K. L. Felch, B. G. Danly, H. R. Jory, K. E. Kreischer, W. Lawson, B. Levush, and R. J. Temkin, "Characteristics and applications of fast-wave gyrodevices," *Proceedings of the IEEE*, vol. 87, no. 5, pp. 752–781, 1999.
[68] 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 International Conference on*. IEEE, 2008, pp. 1–2.
[69] S.-T. Han, R. 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 Photonics, 2006, pp. 63 730C–63 730C.
[70] M. K. Hornstein, V. S. Bajaj, R. G. Griffin, K. E. Kreischer, I. Mastovsky, M. A. Shapiro, J. R. Sirigiri, and R. J. Temkin, "Second harmonic operation at 460 ghz and broadband continuous frequency tuning of a gyrotron oscillator," *Electron Devices, IEEE Transactions on*, vol. 52, no. 5, pp. 798–807, 2005.
[71] 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 gyrotron for enhanced nuclear magnetic resonance," *Plasma Science, IEEE Transactions on*, vol. 38, no. 6, pp. 1150–1159, 2010.
[72] R. McMillan, "Terahertz imaging, millimeter-wave radar." in *Advances in Sensing With Security Applications*, J. Bymes, Ed., 2006, pp. 243–268.
[73] M. Kartikeyan, E. Borie, and M. Thumm, *Gyrotrons: High power microwave and millimeter wave technology*. Springer Verlag, 2004.
[74] G. Nusinovich, *Introduction to the Physics of Gyrotrons*. Johns Hopkins Univ Pr, 2004.
[75] E. Schamiloglu, "High power microwave sources and applications," in *Microwave Symposium Digest, 2004 IEEE MTT-S International*, vol. 2. IEEE, 2004, pp. 1001–1004.
[76] 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.
[77] 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,*

Springer, vol. 32, no. 5, pp. 402–405, 2006.

[78] A. Roy, J. Mondal, R. Menon, S. Mitra, D. Kumar, A. Sharma, and K. Mittal, "High power microwave generation from coaxial virtual cathode oscillator," in *Proceedings of the Asian Particle Accelerator Conference*, Indore, India, 2007, pp. 523–525.

[79] I. Salama, C. Middleton, N. Quick, G. Boreman, and A. Kar, "Laser-metallized silicon carbide schottky diodes for millimeter wave detection and frequecny mixing," in *State-of-the-Art Program on Compound Semiconductors XXXIX and Nitride and Wide Bandgap Semiconductors for Sensors, Photonics and Electronics IV: proceedings of the international symposia*, vol. 2003. The Electrochemical Society, 2003, p. 270.

[80] V. Ilchenko, A. Matsko, A. Savchenkov, and L. Maleki, "High efficiency microwave and millimeter wave electro-optical modulation with whispering-gallery resonators," SPIE, 2000.

[81] L. Johansson and A. Seeds, "Generation and transmission 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.

[82] S. Voingescu, "Mm-wave in cmos – opportunities above 50 ghz?" in *CMOS Emerging Technologies Workshop*, Banff, Canada, July 2006.

[83] D. Wake, C. Lima, and P. Davies, "Optical generation of millimeter-wave signals for fiber-radio systems using a dual-mode dfb semiconductor laser," *Microwave Theory and Techniques, IEEE Transactions on*, vol. 43, no. 9, pp. 2270–2276, 1995.

[84] B. Razavi, "A millimeter-wave circuit technique," *IEEE Journal Of Solid-State Circuits*, vol. 43, no. 9, pp. 2090–2098, September 2008.

[85] R. Miyamoto, K. Leong, S. Jeon, and Y. Wang, "Digital wireless sensor server using an adaptive smart-antenna/retrodirective array," *EEE Transactions On Vehicular Technology*, vol. 52, no. 5, pp. 1181–1188, September 2003.

[86] 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.

[87] M. Oodo, R. Miura, and Y. Hase, "Onboard dbf antenna for stratospheric platform," in *Proceedings of the IEEE International Conference on Phased Array Systems and Technology, 2000*, Dana Point, CA, USA, May 2000.

[88] D. Goswami, S. Vijayaraghavan, S. Lu, and G. Tamm, "New and emerging developments in solar energy," *Solar Energy*, vol. 76, pp. 33–43, 2004.

[89] Y. Wang, K. Kempa, B. Kimball, J. Carlson, G. Benham, W. Li, T. Kempa, J. Rybczynski, A. Herczynski, 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.

[90] A. Pham, J. Laskar, V. Krishnamurthy, H. Cole, and T. Sitnik-Nieters, "Ultra low loss millimeter wave multichip module interconnects," *IEEE Transactions on Components, Packaging, and Manufacturing Technology, Part B: Advanced Packaging*, vol. 21, no. 3, August 1998.

[91] 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.

[92] E. Brookner, "Phased array radars-past, present and future," in *RADAR 2002*. IEEE, 2002, pp. 104–113.

[93] V. Raghunathan, A. Kansal, 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.

[94] R. Corkish, M. Green, and T. Puzzer, "Solar energy collection by antennas," *Solar energy*, vol. 73, no. 6, pp. 395–401, 2002.

[95] R. Corkish, M. Green, T. Puzzer, and T. Humphrey, "Efficiency of antenna solar collection," in *Photovoltaic Energy Conversion, 2003. Proceedings of 3rd World Conference on*, vol. 3. IEEE, 2003, pp. 2682–2685.

[96] A. De Vos, *Endoreversible thermodynamics of solar energy conversion*. New York, NY (United States); Oxford University Press, 1992.

[97] B. Berland, L. Simpson, G. Nuebel, T. Collins, and B. Lanning, "Optical rectenna for direct conversion

of sunlight to electricity," *Physics Review*, pp. 323–324, 2003.

[98] H. Ries, "Complete and reversible absorption of radiation," *Applied Physics B: Lasers and Optics*, vol. 32, no. 3, pp. 153–156, 1983.

[99] S. Wright, D. Scott, J. Haddow, and M. Rosen, "The upper limit to solar energy conversion," in *Energy Conversion Engineering Conference and Exhibit, 2000.(IECEC) 35th Intersociety*, vol. 1. IEEE, 2000, pp. 384–392.

[100] M. Green, *Third generation photovoltaics: advanced solar energy conversion*. Springer Verlag, 2003.

[101] B. S. Richards and A. Shalav, "Photovoltaics devices," in *The Handbook of Photonics 2nd Edition*, M. Gupta and J. Ballato, Eds. CRC Press, Boca Raton, Florida, 2007, ch. 8, pp. 8–19.

[102] T. Du Bosq, R. Peale, and G. Boreman, "Terahertz/millimeter wave characterizations of soils for mine detection: Transmission and scattering," *International Journal of Infrared and Millimeter Waves*, vol. 29, pp. 769–781, 2008.

[103] 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.

[104] 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.

[105] 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.

[106] 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.

[107] L. Reddy and B. Reddy, "Some observations on the influence of hydrometeors on line-of-sight microwave propagation at 7 ghz in tropics," in *Proceedings of ISAP'92*, Sapporo, Japan, 1992, pp. 889–892.

[108] G. W. Petty, *A First Course In Atmospheric Radiation*, 2nd ed. Madison, Wisconsin: Sundog Publishing, 2006, no. p. 283.

[109] H. Liebe and G. Hufford, "Modeling millimeter wave propagation effects in the atmosphere," North Atlantic Treaty Organization, AGARD Report 454, 1989.