Program for IEEE WiSEE 2021

Space Solar Power (SSP) Workshop

12-14 October 2021

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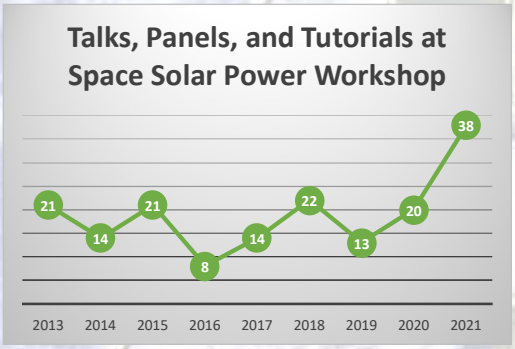
Letter from the Organizers

Welcome all to another roller-coaster-ride of a fall conference season. We really appreciate the effort all contributors and attendees made for this year's Space Solar Power workshop, given the wild pandemic year and the sudden switch to a virtual format.



Great things are afoot in our community! This year the program sees the largest number of contributed talks (38) in its brief history. Active space solar power projects are afoot in Japan, China, and the US, with contributions being made from all across the globe. This year's workshop features two special sedssions on *Additively Manufactured Electronics for Space* and Reflectarrays. Great thanks to the respective organizers of those sessions, Profs. Manos Tentzeris and Andrew F. Peterson. Additional thanks to the IEEE CRFID Technical Committee on Motion Capture and Localization for contributing the content marked MoCap as part of a joint effort.

We are once again grateful to the organizers of the annual IEEE Wireless in Space and Extreme Environments (WiSEE) international conference series for hosting our workshop as part of an enduring partnership that we hope to continue.

Lastly, a special thanks once again to our workshop sponsor, the Space Solar Power Institute (SSPI, https://solarsat.org). We researchers are grateful for SSPI's continued leadership in this field and look forward to many more workshops to come.

Sincerely,

Your enthusiastic organizers,
Gregory D. Durgin, Reza Zekavat, Darel Preble, Christopher R. Valenta

Session IA: Special Session on Reflectarrays (Tuesday, Oct 12, 13:00-15:00 ET)
organized by Andrew F. Peterson and Gregory D. Durgin, Georgia Tech

13:00 ET: *Opening Remarks, Invitation to Publish in IEEE JRFID Special Issue*.
Reza Zekavat, Worcester Polytechnic Institute

Welcome! A special introduction to the 2021 Space Solar Power workshop at IEEE WiSEE 2021.

The Space Solar Power working group, part of the newly formed IEEE CRFID Technical Committee on Energy Harvesting Systems, announces a special issue on Space Solar Power, to be published in 2022 in the *IEEE Journal on RFID*. We will issue an open call for papers in the area, but each IEEE WiSEE 2021 SSP workshop presenter is hereby given a personal invitation to submit a manuscript based on their presentation or extended conference paper.

13:15 ET: *Improvements to Reflectarray Design for Microwave Wireless Power Transfer*.
Evan Shi, Johns Hopkins Applied Physics Lab, Gregory D. Durgin, Georgia Tech

Large-scale wireless power transfer using microwaves is a promising technology for power transmission over distances unsuited for physical wire connections, such as between orbit and the Earth. Using large transmitting and receiving apertures, it is possible to focus microwave energy to achieve efficient transfer. This is accomplished by adjusting the phase distribution across the surface of the transmitting array such that it behaves like a Fresnel lens. One method of generating the desired phase distribution is through use of an active reflectarray, comprised of many discrete 2-dimensional unit cells with varying reflection coefficient phases. This work investigates the effect of changing the unit cell geometry from square to hexagonal, modifying the individual patch element geometry, and incident pilot signal design for the reflectarray.

13:30 ET: *3D Printed Deployable Origami-inspired Dielectric Reflectarray Antenna with Beam-scanning Ability.*
Yepu Cui, Georgia Tech

A first-of-its-kind, fully 3D printed mm-wave reflectarray with deployability and beam-scanning ability will be presented in this session. It consists of an array of origami-inspired flat-foldable dielectric-based unit cells featuring an unprecedented reduction in volume as compared to its conventional counterparts. The outcome of this work demonstrates a low-cost, high-

performance dielectric reflectarray design that can be folded to 1/3 of the full-scale volume which can be used for outer-space, 5G, and various other applications.

13:45 ET: *Design of Circularly Polarized Mechanically Reconfigurable Reflectarrays for Satellite Communications and Power Transfer.*
Joshua Roper, ViaSat, Andrew F. Peterson, Georgia Tech

This paper presents a methodology for designing circularly polarized mechanically reconfigurable reflectarrays with applications to wireless power transfer. It presents some basic theory on spectrally limited power transfer (i.e. how carrier tapers of non-timed arrays can lower channel efficiency). It derives a similarity transformation that converts the linearly polarized Floquet scattering matrix of a periodic unit-cell into right-handed and left-handed circular polarization. This technique leverages the conventional Jones basis and unity matrix for linear and circular polarizations and is inspired by radar polarimetry which has a similar congruence transformation. To illustrate the concepts, a concentric split-ring reflectarray unit-cell is designed, optimized, and simulated for the entire Ku-band. The proposed design is ultra-wideband over the 10 GHz to 15 GHz range and has low loss and depolarization properties. The unit-cell is used in a full reflectarray and simulated in Ansys HFSS to get directivity patterns for various frequencies.

14:00 ET: *Power Transmission using Reflect and Transmit Array Configurations*,
Atef Elsherbeni, Colorado School of Mines

Power transmission is one of the most emerging technology for many recent and advanced applications such as remote sensing, radar, medicine, imaging systems, and IoT. Most of these applications require near field communications through power transmission. Focused antennas which concentrate electromagnetic radiated power at a small spot in the near field or in a specific direction in the far field are key to these applications. While many different types of antennas, such as reflectors, lenses, and arrays, can be focused, arrays have the highest degree of design freedom, and thus have received the most attention.

This talk will demonstrate some of the recent designs of reflectarray and transmitarray antennas that are capable of focusing the radiated field in the near field region of the antenna. Focusing characteristics of reflectarrays are investigated and a focused reflectarray system achieving 30° scan is demonstrated. It is shown that a focused reflectarray can be a good candidate for limited field-of-view applications. The basic procedure to design focused transmitarray antennas is also presented and demonstrated through a tranmitarray design focusing the transmitted power in the near field of the antenna. The focusing characteristics of the transmitarray are also compared to a classic case designed for far-field operation. It is concluded that a focused transmitarray can be a good candidate for applications requiring high power focused microwave energy.

14:15 ET: *Large Phased Spaced Solar Power Satellite Array Guided by Phase-based Tunneling RFID Tags.*
Cheng Qi, Cognosos LLC

Space solar power systems require satellites with solar panels to form a phased array that beams the power towards the base station, while orbiting Earth in geostationary orbit (GEO), about 35,000 km above Earth's surface. A ranging technique that can accurately detect the change of relative distances between the elements in the phased array is critical to provide desired beamforming performance. Tunneling RFID tags have proved their accuracy, sensitivity, and range of operation in terrestrial applications. The use of tunneling tags to fine-tune the phased array in the space is anticipated. This talk will focus on the performance of tunneling tags and how they can be used in space solar power.

14:30 ET: *Panel on How to Achieve Phase Coherence in a Large Array.*
moderated by Andrew F. Peterson, Georgia Tech

Session IB: Special Session on Space Ambient Power (Tuesday, Oct 12, 15:15-16:45 ET)
chaired by Alessandra Costanzo, University of Bologna

15:15 ET: *Smart Beamforming and Focusing for WPT.*
Diego Masotti and Alessandra Costanzo, University of Bologna

This contribution deals with promising solutions of smart radiating systems with agile reconfigurable capabilities. First, the time-modulated array (TMA) family is described, by highlighting: i) its architectural simplicity, being a standard array simply equipped with RF switches controlled in time to activate or not the corresponding antenna; ii) its exploitation in WPT applications for both localization and powering of multiple objects. A two-element TMA prototype allows to demonstrate the high potentialities of this family of arrays. Then, the frequency diverse arrays (FDAs) are presented as an alternative powerful solution for precise WPT. Indeed, the dynamic generation, obtained through frequency diversity, of the array factor can be easily controlled to focus the power at desired distances and drastically reduce it in undesired ones. This is obtained by duty-cycling the FDA excitation signals and by suitably choosing the time delay of the excitation pulse. First the theoretical design of the time- and frequency- dependent array is developed, then it is applied to predict the ranging performances of a 16-element linear array. For validation purposes a demonstrator is implemented through the use of the software defined radio (SDR) Xilinx RFSoC ZCU111 to dynamically generate the needed radio signal excitations of the antenna array. To comply with the SDR, the operating frequency is 1.8 GHz and a 4-element array is used. The preliminary measurements confirm the ranging capabilities of the proposed solution. As a conclusion, an analysis of beampattern performance for bi-dimensional FDA is performed: the multi-finger and circular FDA topologies are presented as potential future solutions for capillary WPT.

Speaker Bio: Diego Masotti (M'00, SM'16) received the Ph.D. degree in electric engineering from the University of Bologna, Italy, in 1997. In 1998 he joined the University of Bologna where he is Associate Professor of electromagnetic fields. His research interests are in the areas of nonlinear microwave circuit simulation and design, with emphasis on nonlinear/electromagnetic co-design of integrated radiating subsystems/systems for wireless power transfer and energy harvesting applications. Dr. Masotti is a member of the MTT-25 Committee on WPT and Energy conversion. He serves in the Editorial Board of the International Journal of Antennas and Propagation, the Hindawi Journal of Wireless Power Transfer, IEEE Access, and Electronics Letters and is a member of the Paper Review Board of the main Journals of the microwave sector.

15:30 ET: *Low-Cost, High-Gain and Wide Angular Coverage Terrestrial Receivers of Space Ambient Power.*
Aline Eid, Georgia Tech

This talk discusses the deployment of Rotman lens-based terrestrial receivers capable of collecting the beamed power from space from a wide angle with high gain. The deployment of a passive beamforming network, such as the Rotman lens, avoids the challenges associated with active, expensive phased arrays implementations that require phase shifters with very high-power handling capabilities. This solution offers a higher degree of freedom allowing for continuous collection of microwave power with little losses regardless of the relative orientations at minimal cost.

Speaker Bio: Aline Eid received her B.Eng. and M.S. in Electrical and Computer Engineering from Notre Dame University, Louaize, Lebanon and the American University of Beirut, Lebanon, in 2015 and 2017, respectively. She is currently a Ph.D. candidate in Electrical Engineering in the ATHENA Group led by Prof. Manos Tentzeris, at the Georgia Institute of Technology. Her research interests are in Electromagnetics and Microwave/Millimeter-Wave Devices and Systems, Intelligent, Autonomous, and Human-aware Systems and Communications and Networking. Her research focuses on zero-power mm-wave-enabled solutions for smart environments and autonomous robots and vehicles. She was the first to propose unconventional fully-printed structures to enable batteryless devices with breakthrough wireless capabilities, by combining knowledge in electromagnetics, antennas, RFIDs, signal processing and materials science. During her Ph.D., Aline was the recipient of more than 12 awards, inventor in 4 patents, and author/co-author of more than 35 conference and journal papers and book chapters.

15:45 ET: *Space-Based Ambient Power for Sensors and Other Low-Power Applications.*
Stewart Thomas, Bucknell University and Gregory D. Durgin, Georgia Tech

Space Solar Power (SSP) may promise to deliver unlimited green energy to the surface of the earth through microwave power beaming, but it suffers from an “all-or-nothing” aspect of its deployment: one cannot begin to reap the benefit from even a test SSP system without billions of dollars of infrastructure launched into space and installed on the ground. However, space ambient power (SAP)—a blanketing of an urban area with very low-level microwave power to drive batteryless sensors, medium-range communication, and other applications— is a much lower-cost proposition that could be used as a proving ground for SSP concepts.

16:00 ET: *Bootstrapping Lunar Exploration to Settlement: Power and Ancillary Services Beaming.*
Gary P. Barnhard and Seth D. Potter, XISP-Inc

The ability to provide power and ancillary services when and where needed is essential to virtually all aspects of human endeavor and enables all forms of space exploration/development/settlement.
Defining an incremental path to realize the necessary power infrastructure to support settlement and its precursor activities is a significant system engineering challenge.

More specifically, it is necessary to determine what are the increments of scalable interoperable modular power and ancillary services needed to support exploration, prospecting, proving reserves, exploitation, habitation, and settlement of the lunar surface, as well as how the requirements for the same can be accommodated. In addition, each power and ancillary services increment can provide the necessary power and services needed to construct the next increment.

The current state-of-the-art with respect to surviving and operating through the night on the lunar surface is profoundly limited. While there are multiple terrestrial and even space qualified technologies that could be leveraged to design viable end-to-end power generation, storage, and distribution systems suitable for the lunar environment, the systems engineering of the same is nascent.

This paper will curate/generate, intersect, and converge multiple technology development efforts to yield a recommended set of deployable power and ancillary services beaming infrastructure payloads. The first data set is the Vendor User's Guides for the NASA Commercial Lunar Payload Services (CLPS) contract lunar lander spacecraft and the data on the anticipated Human Landers. The second data set is the customer requirements of prospective payloads which are broken into four increments. The first scalable modular increment of power services for initial exploration can be defined as up to 1 kW, a second more expansive increment to 10 kW supporting prospecting, a third increment to 100 kW proving reserves, and a fourth increment to 1,000 kW supporting exploitation, habitation, and settlement. The third data set is the accumulated theoretical/experimental test data on transmitter options, the rectenna/receiver options, and the end-to-end efficiency for microwave, millimeter wave, and infrared/optical frequencies.

Working from the potential available input power increments, a similar scaling can be deduced. The DC-to-Beam conversion efficiency factored in, yielding estimates for the maximum power output electrical and the maximum power output thermal. Using the collection efficiency method, the received power can be calculated for various distances of interest. The resulting values will be translated into power and ancillary services infrastructure designs that are both robotic and EVA compatible for peer review. This updates Virtual IAC2020 work.

16:15 ET: *Panel on Space-Based Ambient Power.*
Moderated by Alessandra Costanzo, University of Bologna

Session IIA: Special Session on Additively Manufactured Electronics in Space (Wednesday, Oct 13, 13:00-15:00 ET), organized by Manos Tentzeris and Gregory D. Durgin, Georgia Tech; chaired by Christopher R. Valenta, Georgia Tech Research Institute

13:00 ET: *3D-Printed Microfluidic Sensors for Satellite Health Monitoring.*
D. Henry, T. Marchal, A. El Sayed Ahmad, P. Pons, Herve Aubert, LAAS Toulouse

Geostationary satellites use more and more sensors to monitor the satellite health. Sensors may be used, e.g., for the thermal or mechanical monitoring of the external surfaces of satellites, where antennas are located. To reduce the consumption of on-board electric power, electromagnetic harvesting techniques have been reported by our research team in 2013 for supplying DC power to temperature sensors placed on satellite panels. Moreover, the use of dual-polarized passive repeaters has been recently proposed by us to wirelessly interrogate fully passive sensors located inside the satellite structure. We propose here a new approach for Satellite Health Monitoring, which consists of using a polarimetric millimeter-wave radar imagery technique to remotely identify and read passive sensors deploying on the satellite surfaces. The proposed solution uses wireless and depolarizing sensors manufactured from additive and microfluidic technologies. First investigations and experimental results will be presented at the Workshop.

13:15 ET: *On-Orbit Polymer Mass Loss Results from MakerSat-0 and MakerSat-1 Missions.*
Connor Nogales, Braden Grim, Mitch Kamstra, Ben Campbell, Joshua Griffin, and Stephen Parke, Northwest Nazarene University

MakerSat-1 utilized a specially designed frame 3D printed out of ABS on board the International Space Station (ISS). MakerSat-1 was launched to the ISS on Dec. 5th, 2019 on the SpaceX CRS-19 Dragon and deployed from the ISS on Jan. 31, 2020. MakerSat-0 utilized an aluminum frame provided by Near Space Launch Inc. (NSL) and was launched on November 17th, 2017 from Vandenberg Air force Base on a Delta II rocket. MakerSat-0 and MakerSat-1 performed on-orbit measurements of the mass loss of various 3D printed polymers during the life of the satellites, in order to characterize the polymers for potential space application. Polymers undergo mass and structural degradation in space due to outgassing, ionizing radiation, monoatomic oxygen radicals, and even micro-meteor impacts. Characterizing the degradation contributed by each of these mechanisms is difficult, however, an overall degradation metric can be determined through the overall mass loss of the material. This was the objective of the MakerSat-0 and MakerSat-1 science payload. MakerSat-0 measured a mass loss of 40.3% in Nylon, 17.0% in

ULTEM, and 0% in PLA over a two-week mission window. The results from MakerSat-1 roughly matched the two-week data from MakerSat-0 and after four months revealed a mass loss of 26.5% in ABS, 20.9% in ULTEM, and 9.9% in PLA.

13:30 ET: *Additive Manufacturing RF Components for Space Solar Power*.
Prof. Manos Tentzeris, Georgia Tech

In this talk, inkjet-/3D-printed antennas, interconnects, "smart" encapsulation and packages, RF electronics, microfluidics and sensors fabricated on glass, PET, paper and other flexible substrates are introduced as a system-level solution for ultra-low-cost mass production of Millimeter-Wave Modules for Communication, Energy Harvesting and Sensing applications.

13:45 ET: *Transparent Rectenna Design for Space Solar Power Applications*
Thomas Rodriguez, Georgia Tech

The shift from hydrocarbon-based fossil fuels has sparked an increase in demand for alternative energy sources. Space solar power in theory can be an extremely renewable resource since it works the same as normal solar panels, but now it is transmitting the power via microwaves to a ground station. This paper illustrates possible designs for a ground station portion of a space solar power system. There are two main aspects of this project: designing a circularly polarized patch antenna and determining a geometry for the patch antenna array and designing a dual-stage rectifier. The reason for designing a circularly polarized antenna is to reduce the amount of cross polarization and thus increase the amount of power received from the solar powered satellite. In theory, a dual-stage rectifier has a higher power efficiency compared to a single stage rectifier when receiving a high input power, which is why it was chosen as the design. Also, it would be able to have a higher output voltage due to an extra stage in the charge pump.

14:00 ET: *An Overview of Optically Transparent Antennas and Applications to Space Solar Power*.
Zachary J. Silva, Sandia National Laboratory, Christopher R. Valenta, GTRI

Optically transparent antennas have been rapidly inserted into next generation antenna designs for antennas on vehicle windows, integrated into phone screens, and on solar panels of CubeSats and SmallSats. The competing requirements for high optical transparency and low sheet resistance in optically transparent antennas make the problem extremely challenging. With continuous advancements in material science and manufacturing, high performing optically transparent conductors are becoming readily available to the modern antenna designer. The presentation will discuss the past, present, and future of optically transparent antennas and give perspectives on upcoming possible applications, challenges, and use cases for Space Solar Power. Utilizing high performing optically transparent conductors patterned and

embedded into a solar panel enables a dual-use aperture for harvesting solar power while also radiating RF energy back down to Earth.

14:15 ET: *Quasi-Geostationary Earth Orbits for Space Solar Power Infrastructure and Other Low Area Density Satellites*.
Gregory D. Durgin, Georgia Tech

Earth-orbiting *low area density satellites* (LADsats) -- satellites with a mass-to-cross-section-area ratio of less than 10 kg/m^2 -- experience significant solar pressure forces that result in non-Keplerian astrodynamics. This paper outlines the behavior of semi-stable *quasi-geostationary earth orbits (*QGEOs*)* that allow LADsats to navigate with minimal station-keeping. With natural protections against burdening space with debris, the LADsat portends not only an economical mode of design for large pieces of space infrastructure like space solar power satellites, but also a paradigm for even small satellite designs that protect valuable orbital space around planet earth from debris.

14:30 ET: *Panel on Additively Manufactured Electronics in Space.*
Moderated by Christopher R. Valenta, Georgia Tech Research Institute

Session IIB: Power Systems and Economics (Wednesday, Oct 13, 15:15-16:45 ET), chaired by Gregory D. Durgin, Georgia Tech

15:15 ET: *Virtus Solis Technologies' Approach to Space Solar Power*.
John Bucknell, Virtus Solis

High Energy Return on Investment (EROI) is a key contributor to economic growth and universal prosperity. Our planet has benefitted from over two hundred years of industrialization and increased standards of living based largely upon high returns from low extraction and distribution costs of fossil fuels. Unfortunately, these energy resources are not equitably distributed, and strife related to lack of access to the benefits of low-cost energy has been constant. These facts, in addition to the impacts on health from extraction and combustion of fossil fuels as well as the rising desire to reduce atmospheric greenhouse gasses has increased the penetration of what had been called alternative and now sustainable clean energy sources. Advocates for sustainable energy have concluded that wind, water, solar, and (for some) nuclear energy can displace fossil fuels – especially with the advent of commercial electrified energy storage.

The challenge with a transition to fully sustainable energy is economics. The costs associated with a transition to sustainable electrification have led to high energy costs in markets that have invested heavily in wind and solar absent energy storage (particularly, Germany and California), due to the need for dispatchable energy (usually high cost) that can offset the inherent intermittency. Nuclear power has a legacy associated with weapons, large regulatory overhead costs and manufacturing methods that drive costs of licensed systems to extremely high Levelized Cost of Energy (LCOE). We believe these facts, compounded with the lack of scalability of battery energy storage dooms electrification plans to high energy costs for most if not all markets. An alternative solution is needed to provide the large lever for universal prosperity that is low cost, clean, and always available energy.

Space Based Solar Power (SBSP) plans to date have not satisfied the EROI and consequently the LCOE needed to be an economically competitive source of energy despite the advantages of being baseload-capable, clean, sustainable, and dispatchable generation. Early concepts required investment in off-planet manufacturing and feedstocks to avoid launch cost overhead. This is circular logic, as launch costs to place manufacturing capacity as well as operations and maintenance personnel and their habitats off-planet represent an enormous investment without any return for decades. The magnitude of that required for investment puts the SBSP solution in the category of nation-state level of investment, and in fact the People's Republic of China has recently declared plans to do just that in conjunction with the announcement of a new heavy lift rocket. As part of a plan to expand in-space infrastructure, Virtus Solis

Technologies has developed an approach to SBSP that avoids the capital expenditure associated with prior approaches that yields the lowest LCOE of energy on the planet.

Speaker Bio: John R. Bucknell, CEO and Founder of Virtus Solis Technologies graduated from Cleveland State University in 1995 with a Bachelor's in mechanical engineering and the University of Michigan in 1999 with a Master's in systems engineering. John is a serial entrepreneur with 26 years industry experience in bringing energy conversion systems to market including four production internal combustion engine families and nine years of aerospace engineering design including design of the Raptor rocket engine for SpaceX. He has held posts in Advanced Powertrain at both General Motors and FCA and was most recently Director of Propulsion and Electrical Engineering at Divergent Technologies where he led the development of the 1250bhp strong hybrid powertrain for the Czinger 21C. John holds 46 patents and has two technical publications in the fields of air breathing combined cycle rocket design (both nuclear and chemical-based), one in high thermal efficiency transport engines, one in synthetic fuel production through ocean thermal energy and a proposal describing co-production of electricity and synfuel with molten salt nuclear reactors.

15:30 ET: *Implications of Designing a Space Solar Power System Using Realistic Electrical Energy Demands.*

R. Madonna[1], M. Marshall[2], A. Kukreja[3], S. Pellegrino[2] ([1]System Engineering Consultants, [2]Cal Tech, [3]John P. Stevens High School in Edison NJ.)

We explore the implications of designing space solar power (SSP) systems to satisfy realistic electrical energy demands. Most of the previous studies assumed that providing constant power to a city or metropolitan area is sufficient to ensure economic viability in that all the energy produced is used at time of production. Electrical energy demands from various utilities show that the demand varies with time of day and time of year, thus undermining the notion that all the energy generate is consumed. We use demand data from New York City to design SSP systems with focus of our designs being the California Institute of Technology Space Solar Power Project (SSPP) architectures that we are developing. Using an extension of the guidance and control laws developed in previous works, we simulate a year of supplying energy to New York using three different case for the amount of energy delivered daily. The key findings that emerge from our study are: 1. Long term utility scale storage is required, regardless of the architecture of the space power station – some is necessary to smooth daily fluctuations while the majority is needed to satisfy seasonal peak demands; 2. Designs generating energy in excess of demand run the risk of effectively higher LCOEs as there is no assurance that some or all of the excess can be sold; and 3. Opting to design a system to provide a constant bae supply of energy still results in production of excess energy, hence a risk for increasing the LCOE if the excess cannot be sold.

15:45 ET: *Energy Economics Update: Perspective 2021*.
Gail Tverberg, Our Finite World

In 2021, the world economy was supposed to bounce back from the pandemic of 2020, but this is not happening as strongly as hoped. While there is still some possibility that strong growth will return, there is also a possibility that the world economy is entering a permanent mode of shrinkage, with falling oil and coal extraction. It was hoped that prices would rise high enough to maintain production levels of these fuels for many years, but it is becoming less clear that this will happen. This talk will give some ideas on how Space Solar could be affected.

16:00 ET: *US Power Grid Stability, Reliability, Resilience, Security and ... our next Giant Leap*.
Darel Preble, Space Solar Power Institute

It is many years past the time when our US Congress and President should have chartered Space Solar Power (SSP) enabling legislation to create a public-private "SUNSAT Corporation" with the financial, technical, legal and political wherewithal to truly respond to our surging CO2 induced climate change; energy security; energy economics; and environmental security problems.

Speaker Bio: Darel Preble is President and Executive Director of the Space Solar Power Institute in Atlanta, GA. He holds degrees from Ga State, George Washington and Vanderbilt Universities. He is married, in excellent health, is a member of Peachtree Church and enjoys reading, writing, speaking, hiking, and surfing without a board to stand on.

16:15 ET: *Panel on the Business Case for SSP*.
Moderated by Gregory D. Durgin, Georgia Tech

Session IIIA: Novel Concepts I (Thursday, Oct 14, 13:00-15:00 ET), chaired by Brian Gunter, Georgia Tech

13:00 ET: *Orchestrating Symbiosis: Foundational technologies for Human, Robotic, and Autonoma Shared Control – Exploring the Framework.*
Gary P. Barnhard, XISP-Inc

All those involved in understanding, architecting, and implementing shared control relationships between humans, robotics, and autonoma need a framework that encompasses both the problem space and provides for articulating non-null solution spaces which are both satisfactory and sufficient. Motivating and embracing worldviews that allow for the same will challenge our expectations in no uncertain terms.

In the most general sense, the Problem Space is that of N-Dimensional interaction problems (i.e., an arbitrary number of objects inter-acting in an arbitrary number of ways). These are a class of problems for which the generalized solution space is typically computationally intractable in any time frame. Space autonoma and robotics present a subset of these problems that exacerbates the situation by requiring near real-time solutions in many instances. Alas, "reality" is not a convenient problem or solution space.
Accordingly, this leaves us in a quest to find nexus: in this case, the intersection between theoretical constructs of knowledge-based systems and space systems engineering reduced to practice. The mission development efforts presented can be viewed as a set of conceptual threads intended to draw out the confluence of interests needed to bias work towards better "outcomes" for Cislunar and beyond space missions.

The core set of XISP-Inc Technology Development, Demonstration, and Deployment (TD^3) missions development work include five synergistic elements all of which have some intersection with the WiSEE portfolio of interests:

- Space Solar Power and ancillary services Beaming (SSPB)
- Interoperable Network Communication Architectures (INCA)
- Management Operations Control Architecture (MOCA)
- Halfway To Anywhere (HTA)
- Alpha Cube Sat (ACS)

Creating a framework and foundation for a mutable locus of shared control is an investment in a positive future, not a dystopian one. How we come to own our own choices, take responsibility for our own actions, and be stewards for life as we come to understand it will define our species.

In the near term, our success in building a symbiotic relationship between humans, robots, and autonoma will be a crucial driver in developing Cislunar space. In the long term, our success in the same could prove to be a determining factor in the fate of our species.

13:15 ET: *Laser Power Beaming Characterization Using Single- and Double-Junction GaAs Photovoltaic Cells.*
Vladislav Yakovlev and Dominik Doktor, Texas A&M

Laser power beaming enables wireless power transfer in free-space, bypassing the need for extensive physical infrastructure. A distinct quality of laser power beaming, when compared to other far-field wireless power transfer methods, is the innate ability to direct kilowatts of power across several kilometers. While there are advantages, power conversion efficiencies tend to be lower than near-field alternatives. A major contributing factor is the photovoltaic cell efficiency, responsible for converting light to electricity. To get a better understanding of the performance of these photovoltaic cells and how they impact laser power beaming, a comparison of single- and double-junction GaAs photovoltaic cell performance is characterized and evaluated.

13:30 ET: *Analysis of On-Orbit Assembly Methods of Interlocking Spacecraft Structures.*
Miles Turner, Martin Davisson, and Brian Gunter, Georgia Tech

Solar Power Satellites (SPS) are an expected, future sustainable energy system. It can convert solar energy to radio frequency (RF) energy and direct the energy to specified locations. While the concept of SPS has advantages, issues arise with the construction and maintenance of these systems in space due to the proposed sizes of such structures being on scales larger than 1 km^2 for Earth-use cases. This paper analyzes the dynamics of the independent-spacecraft assembly method, ISA, and the depot-and-worker assembly method, DWA, for the building and maintenance of future large SPS. The analysis comprises three simulations performed using the orbital dynamic simulation software, 42, for each assembly method to convert a 9x1x1 space structure to a 3x3x1 space structure at a target distance of 5, 50, and 100 meters from the orbital delivery location. In all simulations, the total time, flight maneuvers, and Δv are recorded and analyzed to evaluate each assembly method. The simulations show that the depot and worker assembly method can convert the 9x1x1 space structure to a 3x3x1 using 50% more time, spacecraft maneuvers, and Δv when compared to the independent spacecraft assembly method. These results suggest that when considering only the total time, the number of spacecraft maneuvers, and Δv, the independent spacecraft assembly method is preferred for constructing and maintaining a large Solar Power Satellite.

13:45 ET: *Constrained Admissible Regions for Time Difference of Arrival Orbit Determination.*
Steven Dumas, AFRL

The recent proliferation of low-cost cubesats and smallsats has made urgent the need to identify spaceborne RF emitters, intentional and unintentional jammers, and space debris. This work provides the theoretical framework for identifying the location and orbits of RF emitters using other space-based receivers. This approach is a first-time synthesis of time-difference of arrival (TDOA) RF localization and the constrained admissible regions (CARs) technique, originally used for orbit determination in optical astronomy.

14:00 ET: *Space Traffic Management Perspectives on Space Solar Power.*
Megan Birch and Christopher R. Valenta.

As the number of objects in space has increased in recent years, the number of conjunction warnings for possible collisions between space objects has also grown significantly. However, formal guidelines to manage or coordinate responses to these warnings have yet to be adopted. As both industry and government agencies across the globe seek to utilize the near-Earth space environment with a variety of large planned satellite constellations, the total number of resident space objects (RSOs) is projected to increase by a factor of five in the coming decade, with over 20,000 new satellites in Low Earth Orbit (LEO) and Middle Earth Orbit (MEO) projected to be launched into orbit. This growth is expected to lead to further increases in the number of potential conjunctions. While mission operators strive to ensure all satellites are operational, a certain percentage of these satellites will fail prematurely, creating inactive Resident Space Objects (RSOs) that may stay in orbit for years or decades, creating additional hazards not capable of maneuvering. While guidelines are in place for expected deorbit timelines after a satellite's end-of-life, e.g., 25 years, there is still no formal or widely accepted maneuver guidelines to ensure a future crowded LEO and MEO environment can be effectively managed. In the event a conjunction is predicted, the current system relies on satellite operators acting independently, with no requirement for action or for coordination with other operators or agencies. When considering large, space solar power (SSP) spacecraft in orbit, the current collision predictions will also greatly increase. More so, the large size of the structure may cause challenges in both performing collision avoidance maneuvers as well as these maneuvers causing additional conjunctions. This talk presents an overview of space traffic management, challenges foreseen with incorporating space solar power satellites into the current traffic pattern, and recommendations moving forward.

14:15 ET: *Power Systems Engineering Infrastructure: Scalable Interoperable, EVA and Robotic Compatible Power Generation, Storage, and Distribution Systems for Cislunar Space.*
Gary Barnhard, XISP-Inc

The ability to provide sustainable power and ancillary services when and where needed is essential to virtually all aspects of human endeavor and enables all forms of space exploration, development, and settlement. Architecting the problem/trade space for the same in a manner which supports the definition of scalable interoperable, EVA and robotic compatible power

generation, storage, and distribution systems for use throughout Cislunar space (LEO through to the Lunar Surface and beyond) is the critical focus of this paper.

Starting with a top-level functional block diagram of all extent end-to-end power generation, storage, and distribution system technologies with specific interface planes coded by Technology Readiness Level (TRL) the problem space will be defined. The functional block diagram will be then be exploded to detail the flows across each interface plane on a first principles basis for those technologies which have TRLs suitable for the intended application venues.

Subsequently, the necessary sub-elements required to support the flows across each interface plane will be developed for some number of the intended application venues. The intention is draw out novel approaches to infrastructure development which leverage available technology development work (space and terrestrial), synergies and commonality (both between different technologies and system elements), and thereby help mitigate cost, schedule, and technical risk associated with their application. This approach is anticipated to lead to Power Systems Integration Standards including both accommodation requirements and interface design standards. This body of work will draw from and is directly analogous to the work on the ISS robotic systems integration standards and external utility port convergence efforts which the author was responsible for.

This work will draw from and build on previous work by the author and colleagues associated with technology development, demonstration, and deployment mission development including power and ancillary services beaming, convergence of solar dynamic and compact nuclear fission heat engine technologies, In Situ Resource Utilization (ISRU) processing, Cislunar power systems conceptual analysis, and commercial lunar propellant architectures. This paper revises and extends the Virtual IAC 2020 presentation.

14:30 ET: *Panel on Building Large Infrastructure in Space*.
Moderated by Brian Gunter, Georgia Tech

Session IIIB: Novel Concepts II (Thursday, Oct 14, 15:15-16:45 ET), Moderated by Seyed (Reza) Zekavat, WPI

15:15 ET: *Strange Bedfellows: Space Solar Power's Relationship to the IEEE Council for RFID*,
Gregory D. Durgin, Georgia Tech, and Stewart Thomas, Bucknell University

We provide a brief history and update on the relationship between the IEEE Council for RFID and the Space Solar Power community. The Council is a unique multidisciplinary cooperative of 15+ IEEE Societies that, due to its "silo-busting" structure, has the right blend of technical expertise to address the myriad systems issues faced by Space Solar Power. In particular, we introduce the new IEEE Council on RFID Technical Committee on Energy Harvesting Systems (TC-EHS). This multi-disciplinary committee consists of multiple working groups, one of which is a dedicated Space Solar Power group.

15:30 ET: *Experimental Results and Analysis of Microwave Power Transmission Demonstration System for SSPS*.
Yazhou Dong, Shiwei Dong, Ying Wang, Xiaojun Li National Key Lab. of Science and Technology on Space Microwave

A microwave power transmission demonstration system is proposed to comprehensively simulating the operating mode of MPT in SSPS (Space Solar Power Station). The system consists of three main parts: microwave power transmitting subsystem, microwave power receiving and rectifying subsystem, and power beam control subsystem. The experiment of high power and far distance microwave power transmission based on phased array system has been conducted. The sizes of the transmitting antenna array and rectenna array are 1.2m × 1.2m and 2m × 2m, respectively, and the transmission distance is over 30m. The transmitting power is greater than 900W, the beam control accuracy is better than 0.44°, and the MW-to-DC conversion efficiency of the rectifier array is over 49%. The demonstration system attempts to validate the functions and efficiency of MPT technologies towards SSPS. The research outputs can be the promotion of SSPS development.

Speaker Bio: Yazhou Dong received the B.S. degree from Xi'an Jiaotong University, Xi'an, China, in 2006, and the M.S. degree from Southeast University, Nanjing, China, in 2009. He is a Senior Engineer with the National Key Laboratory of Science and Technology on Space Microwave, China Academy of Space Technology, Xi'an, China. He is also a Ph.D. candidate in the School of Electronics and Information, Northwestern Polytechnical University, Xi'an, China.From Dec. 2017, He has been a Visiting Researcher in University of Kent, UK, supported by China Scholarship Council. His current research interests include space microwave technologies powered by microwave power transmission, microwave power combining, and antenna array technology.

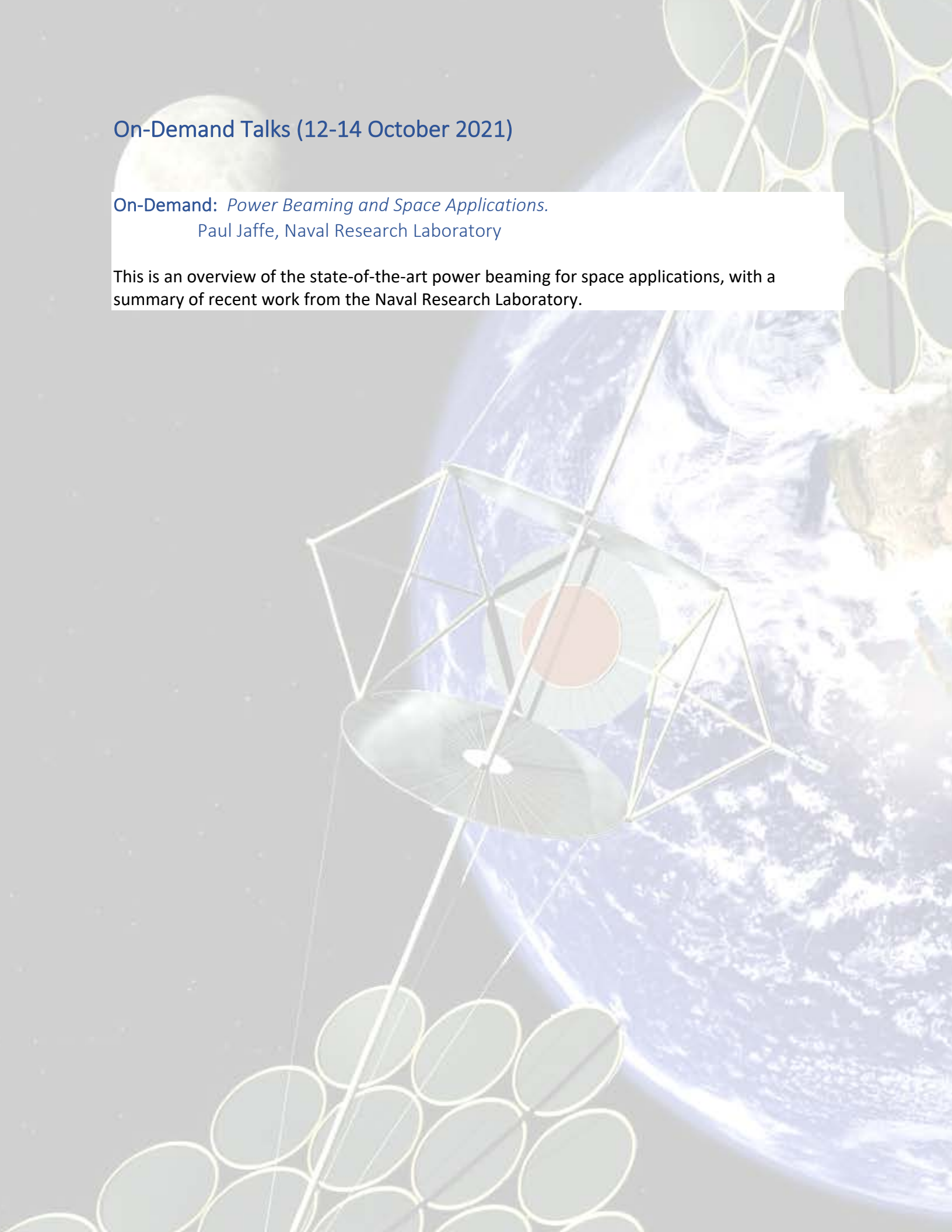
15:45 ET: *Recent R&D Projects and Roadmap toward SPS in Japan.*
Naoki Shinohara, University of Kyoto

In Japan, recently there are two big R&D progects toward the Solar Power Satellites (SPS). One is the development of a sandwich module within a microwave power transfer system, which is in Phase III of R&D supported by METI. The other is a satellite experiment of expanding structure in 2022-23 by JAXA. I introduce both Japanese R&D and roadmap toward the SPS.

16:00 ET: *All-Electric Aircraft Mm-Wave High-Speed and Low Cost Mid-Air Recharging: Satellite and Aircraft Array Configuration Study*.
Shu Ting Goh, National University of Singapore

The all-electric aircraft (AEA) has the potential to assist the aviation industry to achieve zero carbon emission by 2050. However, the AEA's operation range is heavily affected by payload weight and available energy source. Mid-air recharging (MAR) has been proposed as an alternative energy source to reduce the AEA battery payload. MAR utilizes space solar power (SSP) satellite to transfer energy via radiofrequency (RF) wave to rectenna array installed on AEA. This allows AEA to recharge its battery during cruising phase. However, based on International Telecommunication Union (ITU) radio regulation database, only a few frequency bands are freely available for wireless power transfer (WPT) applications. In addition, rectenna arrays of AEA and the antenna arrays of SSP satellite should be carefully designed to minimize the energy loss due to atmospheric attenuation and free space path loss. This paper analyzes the configuration of AEA rectenna arrays and the SSP satellite for various frequency. This analysis considers SSP to AEA atmospheric attenuation and its variation with frequency, and AEA's rectenna array is designed for various commercial aircrafts. In addition, the dimension of SSP satellite's antenna array is studied for different frequency bands based on the given AEA's rectenna array configuration. Moreover, based on the recommendations of ITU, certain frequency bands will be recommended for SSP satellite to AEA power transfer. The study specifically highlights that millimeter wave (mm-wave) and beyond enables low-cost and high-speed AEA MAR. The paper sheds light to solid capabilities of mm-waves as main enabler of AEA MAR technologies.

16:15 ET: *Panel on International Efforts in Space Solar Power*.
Moderated by Seyed (Reza) Zekavat, WPI



On-Demand Talks (12-14 October 2021)

On-Demand: *Power Beaming and Space Applications.*

Paul Jaffe, Naval Research Laboratory

This is an overview of the state-of-the-art power beaming for space applications, with a summary of recent work from the Naval Research Laboratory.

IEEE WiSEE 2022 Workshop on Space Solar Power – Preliminary Call for Participation

This workshop offers a forum for researchers, developers, and policy-makers to discuss SSP technologies, to advance the state of the art, to discuss supporting and related technical issues, and to take necessary actions. Accepted papers will be published at *IEEExplore* and presented at the workshop. The workshop accepts abstracts + talks and papers + talks. Papers should be submitted online and follow IEEE WiSEE 2022 format and submission approach.

Topics Include

SSP communication interference studies
wireless/microwave power transfer
technological and policy for promoting SSP
education at all levels
comparative energy economics
green energy alternatives
energy, space, environmental policy makers
SSP channel modeling/wireless system design
array technology for power transmission
terrestrial power-beaming technology
antenna and solar integration
additive manufacturing for space
astrodynamics for LADsats
transmission modulation, multiple access, freq.
wireless power distribution (all forms)
orbital security and space debris
system structural architecture
packaging and assembly in space
attitude determination and station keeping
energy collection concepts and designs
high-powered microwave and mm-wave sources
space-hardening / in-space system performance
thermal management
SSP manufacturing
environmental impact / planetary sustainability
reflectarrays for power transmission

Check the IEEE WiSEE 2022 website for announcements, conference program, and more. Participation and attendance in the SSP Workshop is included for IEEE WiSEE 2022 registrations.

IEEE WiSEE 2022 will be in Winnipeg, MN, Canada
11-13 October 2022