

Space Solar Power (SSP) Tutorial

A Training on Diverse Topics of Energy, Photo Voltaic, Thermal Design, Radiation Environment, RF, Antenna, Robotics, Space Structures

Dec. 11, 12, SSP Workshop @ IEEE WiSEE'18

Space Solar Power (SSP) has been introduced as a key renewable technology. SSP implementation includes considerable research and development in diverse fields. This tutorial aims to educate researchers and professionals in the advanced and diverse areas of Space Solar Power. Many researchers active in the area of SSP will present this Tutorial.

Tutorial Session 1 (2 Hours): Introduction and Motivation; Chair: Zekavat

- SSP Introduction and Motivation (Reza Zekavat: 5 min);
- SSP Security and Economy Impacts (Darel Preble: 30 min);

Abstract:

SSP Overview Part I - SSP, the Space Force for Next Space

Abstract - "Space is essential to the nation's security and prosperity." said Vice President Pence today. Vast progress in SSP technologies are also the seeds for an incredible array of cis-lunar industries. The Space Force will become America's "traffic cop" in space, with an immense role in managing that international cis-lunar *commercial / military* theater, along with the Commerce Dept. What precisely does the Space Force's role require and how should they meet these demands?

SSP Overview Part II - Earth's 2019 Energy Economics

Abstract - Aerospace is eager to build SSP. The electric power customer perspective, however, has been ignored. SSP could address many extremely intractable problems. In the half century since SSP (and MPT) have been studied a band-aid has been placed on a malignant, metastasized cancer - fossil fuel-price-spike caused recessions; crashing electric power reliability and resilience in spite of Trillions wasted on thousands of unnecessary subsidies for mature RPS technologies, PV and windmills; plant nutritional decline due to accelerating CO₂ increase; unfortunately increasingly necessary international military foci on the unstable Mid-East's high profit margin oil fields. We must graduate from the "SSP Sandbox" to chartering a Sunsat Corp.

- Questions (5 min);
- SSP Implementation Concepts (Paul Jaffe: 40 min);

This presentation will provide a top-level overview of how humankind has historically gotten to orbit, the characteristics of generic space systems, and a survey of prominent solar power satellite architectures. A fundamental introduction to space launch and orbit types will be given. Classifications and examples of historical and recent satellites and their subsystems will be discussed. A functional overview for solar power satellites will be addressed. A gallery of some of the dozens of proposed solar power satellite architectures will be reviewed and assessed.

- Questions (5 min);
- SSP Propagation, SSP Frequency Selection, and Orbit Selection (Reza Zekavat: 30 min);

This section reviews SSP microwave signal propagation and frequency selection and the impact of Ionosphere, Troposphere, and Obstacles such as mountains on the received signal. In addition, the issues associated with the LEO, MEO and GEO orbits will be discussed. These orbits are compared in terms of propagation loss, transmission efficiency.

- Questions (5 min);

Tutorial Session 2 (2 Hours): Technologies Essential for SSP – Part 1; Chair: Preble

- Space Robotics and Modularity (Paul Jaffe: 50 min);

This tutorial section will provide a top-level overview of modularity, in-space assembly, and robotics as they pertain to the prospective development and construction of solar power satellites. Definitions and motivations for each of these topics areas will be presented. Examples of modular space elements and approaches will be surveyed. Recent instances of space robotics and in-space assembly techniques will be discussed. Emerging capabilities will be reviewed.

- Questions (10 min);
- Photovoltaic technologies summary for SSP applications (M. Kelzenberg: 50 min)

This tutorial will present an overview of modern solar technologies including thin-film, silicon, and high-efficiency III-V photovoltaics. We will discuss the fundamentals of photovoltaic energy conversion to understand what factors drive the performance and cost of solar cells. We will also give a brief history of the solar industry and describe its state today. We will give particular attention to the solar technologies suitable for use in the extreme environments of space, including earth orbits as well as in deep space. Then, we will describe the history of SSP, and describe some of the various concepts that have been proposed for its realization. We will also discuss the history and the fundamental concepts of wireless power transmission (WPT), the key enabling technology for SSP. We will conclude with a discussion of present-day efforts to realize SSP and an outlook for future applications of photovoltaics and WPT in space.

- Questions (10 min);

Tutorial Session 3 (2 Hours): Technologies Essential for SSP – Part 2; Chair: Preble

- Transmission Technologies for Space Solar Power (Greg Durgin; 50 min);

In this tutorial section, we will highlight the transmission technologies – microwave sources, antenna design, collection site design, and orbital subsystem designs – essential to space-based solar power systems. We will highlight the trade-offs and issues associated with current and emerging technologies, including high-powered sources, solid-state designs, and antenna phasing techniques. We will take a first-principles look at the diffraction limit and how it dictates the geometry, size, and power transmission of transmission systems. Ultimately, we demonstrate how the transmission technology designs are intimately tied to so many other subsystems of a space solar power platform.

- Questions (10 min);
- Rectenna technologies for SSP applications (J. McSpadden: 50 min);

The rectenna is a major subsystem in a wireless power transmission link from a Space Solar Power (SSP) satellite. A rectenna is designed to receive electromagnetic power and convert it into useful direct current (DC) power. Based on its original conception and implementation in 1964 by Raytheon's William (Bill) C. Brown, the basic rectenna element consists of the antenna radiator, filters, rectifying diode, and DC load. Arrays of elements are connected in parallel or series to efficiently combine their individual DC power into voltage or current forms for distribution to a power grid. This tutorial will cover the rectenna's theory of operation, circuit topologies and components, and circuit models. Rectenna element implementations and examples of rectenna arrays will also be addressed.

- Questions (10 min);

Tutorial Session 4 (2 Hours): Other Considerations; Chair: Zekavat

- SSP System resilience/environmental consideration, radiation environment, thermal design (T. Vinogradova: 45 min);

The presentation will give the overview of radiation environment for space solar power systems with proposed operations at LEO, GEO and HEO orbits. Total Ionization Doses (TID) and Displacements Damage Dose (DDD) analysis will presented for different space based solar power system components and examples of architectural system designs. Results will be summarized to evaluate potential system degradation and to perform system trade study

examples, including system mass impact, component degradation and operational lifetime. Future technologies for advanced shielding and radiation hardness components will be discussed.

- Questions (10 min);
- SSP Launch; Transport; Thrusters (Dallas Bienhoff: 45min);

During this session attendees will learn about launch systems, orbit transfer methods and attitude control concepts applicable to Space Solar Power. Launch systems discussion includes current and upcoming vehicles as well as future concepts. Orbit transfer methods include chemical and electric propulsion vehicles. Attitude control concepts will be discussed for various SSP configurations.

- Questions (10 min);
- Closing Remarks (Reza Zekavat and Darel Preble: 10 min);

Tutorial Presenters' Bio



Prof. Seyed (Reza) Zekavat joined the faculty of Michigan Tech's school of Engineering in 2002. He is the founder of the wireless positioning lab at Michigan Tech. that is supported by the National Science Foundation, the Army Research Labs, and National Instruments. He is the Author of the textbook "Electrical Engineering: Concepts and Applications" published by Pearson, and the editor of the book "Handbook of Position Location: Theory, Practice and Advances," published by Wiley/IEEE. Dr. Zekavat has also co-authored two books "Multi-Carrier Technologies for Wireless Communications," published by Kluwer, and "High Dimensional Data Analysis," published by VDM Verlag. He is on the technical program committees for several IEEE international conferences, serving as a committee chair or member. He served on the editorial board of many Journals including IET Communications, IET Wireless Sensor System, Springer International Journal on Wireless Networks, and GSTF Journal on Mobile Comm.. Dr. Zekavat has been on the Executive Committee of multiple IEEE conferences. Dr. Zekavat has founded and co-chaired many Space Solar Power Workshops mostly at IEEE WiSEE conference.



Darel Preble is a systems analyst, physicist and, since 1997, co-chair of the Space Solar Power Workshop. In 1994, 1995 and 1996, while employed as Southern Company's nuclear security analyst, he wrote a series of three annual white papers entitled "Solar Power Satellites (SPS): The Technological Imperative?" These were not done at Southern Company request or expense but were circulated within the electric power industry and aerospace community. Since December, 1984 he had been Sr. Systems Analyst for INCORE, a nuclear class 1 (safety related) IBM mainframe computer code which managed the nuclear burn at Southern Company's PWR nuclear reactors. He created, taught and hired teachers for classes in new technology systems including neural networks and genetic algorithms; initiated and led numerous advanced technology development projects including an advanced weather forecasting evaluation for bulk power marketing; He represented Southern Company at numerous power industry conference and computer forums including EPRI, EEI, and INFORUM. Mr. Preble's first published testimony before the Department of Energy for the "Third Energy Plan", 1980, "Solar Power Satellites – Energy for the Future" was read into the Congressional Record for June 22, 1981. He was honored to be the only foreigner to address the 2005 Japanese Solar Power Satellite Research Society Symposium. He is a member National Defense Industries Association Energy Security Committee, IEEE, Sigma Xi, and SSI.



Dr. Paul Jaffe has been with the US Naval Research since 1994. He has over 24 years of experience in spacecraft integration and electronics development for dozens of space missions, and has been the principal investigator of ground-breaking technology development efforts. He is widely recognized as one of the world's leading experts on space solar and power beaming. He has over 40 journal, conference, and patent publications, and is the recipient of numerous awards.



Michael Kelzenberg is a Senior Staff Scientist at the Space Solar Power Project (SSPP) and a member of the Atwater Research Group at the California Institute of Technology. The SSPP is working to develop ultralight photovoltaics, deployable space structures, and wireless power transmission technologies, with the goal of enabling cost-effective space-based solar energy. His current research areas include space-deployable solar concentrators, thin-film photovoltaics, thermal design, radiation testing, and reliability. Previously, he worked as a research engineer at Escape Dynamics, which sought to develop low-cost space launch rockets powered by beamed microwave energy. He was also a founder of Caelux Corp., a thin-film photovoltaics company. He holds a PhD in Electrical Engineering from Caltech.



Prof. Gregory D. Durgin joined the faculty of Georgia Tech's School of Electrical and Computer Engineering in Fall 2003 where he serves as a professor. He received the BSEE (96), MSEE (98), and PhD (00) degrees from Virginia Polytechnic Institute and State University. In 2001, Dr. Durgin was awarded the Japanese Society for the Promotion of Science (JSPS) Post-doctoral Fellowship and spent one year as a visiting researcher with Morinaga Laboratory at Osaka University. He has received best paper awards for articles coauthored in the *IEEE Transactions on Communications* (1998 Stephen O. Rice prize), *IEEE Microwave Magazine* (2014), and *IEEE RFID Conference* (2016, 2018). Prof. Durgin also authored *Space-Time Wireless Channels*, the first textbook in the field of space-time channel modeling. Prof. Durgin founded the Propagation Group at Georgia Tech a research group that studies radiolocation, channel sounding, backscatter radio, RFID, and applied electromagnetics (<http://www.propagation.gatech.edu>). He

is a winner of the NSF CAREER award as well as numerous teaching awards, including the Class of 1940 Howard Ector Outstanding Classroom Teacher Award at Georgia Tech (2007). He has served as an editor for *IEEE RFID Virtual Journal*, *IEEE Transactions on Wireless Communications*, and *IEEE Journal on RFID*. Dr. Durgin also serves on the advisory committee on the IEEE Council for RFID (ComSoc Liaison). He is a frequent consultant to industry, having advised many multinational corporations on wireless technology.



Dr. McSpadden is an expert in microwave power transmission systems and rectenna design. Working for over 20 years in industry, he has led projects performing system analysis and technology development for various power transmission projects. He has been a Raytheon consultant on power beaming studies for the DoD, DARPA, NASA, universities, and private companies. Dr. McSpadden received his B.S.E.E, M.S.E.E, and Ph.D. diplomas, all from Texas A&M University, in 1989, 1993, and 1998, respectively. Dr. McSpadden has over 25 presentations and published papers in journals, conferences, and magazines on microwave power transmission.



Dr. Tatiana Vinogradova is an Engineering Research Fellow at Northrop Grumman (NG) Corporation, Aerospace Sector. Her major contributions and research interest are in the areas of ionization phenomena in the upper atmosphere, advanced space instrumentation design, performance evaluation under space environmental conditions. She has been involved in the key aspects of operational space based systems at NG as a technical advisor including payload integration and test, early orbit calibration and flight operational support; served as a Principal Investigator for NG research and development efforts. Tatiana authored and co-authored more than 60 scientific and engineering publications in space research with close academic collaboration.



Dallas Bienhoff is the Founder of Cislunar Space Development Company, LLC. His passion is extending humanity throughout and beyond the solar system. He established CSDC in June 2017 to create commercial transportation from low Earth orbit to the Moon's surface and all points in between. Prior to creating CSDC, he was Space Architect, Project Manager, Capture Team Lead and Proposal Manager at The Boeing Company focused on human Space Exploration missions and commercial Space opportunities. Dallas earned his MS in Engineering from Cal State – Northridge and BSME from Florida Institute of Technology.