SSP 2015 Workshop Technical Program: Dec. 14,15, Orlando, FL

Chairs: Seyed (Reza) Zekavat, Michigan Tech, Darel Preble, Space Solar Power Institute

Monday Dec. 14 2015

***Plenary Talks* 8:30-10am**

1. **Ali Hajimiri** (*Caltech*) Space Based Solar Power: Is there a path from science fiction to reality?

   ***Bio**: Ali Hajimiri received his B.S. degree in Electronics Engineering from the Sharif University of Technology, and M.S. and Ph.D. degrees in electrical engineering from the Stanford University in 1996 and 1998, respectively. He is the Thomas G. Myers Professor of Electrical Engineering and Medical Engineering, as well as the Department Head (Executive Officer) for Electrical Engineering at the California Institute of Technology, Pasadena. His research interests are high-speed and high frequency integrated circuits for applications in sensors, biomedical devices, photonics, and communication systems. Prior to joining Caltech, he worked for Philips Semiconductors, Sun Microsystems, and Bell Laboratories. Dr. Hajimiri was selected to the TR35 top innovator's list (formerly TR100) and as the 2014 National Blavatnik Award finalist. He is a Fellow of IEEE and has served as a Distinguished Lecturer of the IEEE Solid-State and Microwave Societies. He is the recipient of Caltech's Graduate Students Council Teaching and Mentoring award as well as the Associated Students of Caltech Undergraduate Excellence in Teaching Award. He was the Gold medal winner of the National Physics Competition and the Bronze Medal winner of the 21st International Physics Olympiad, Groningen, Netherlands. Prof. Hajimiri has authored and coauthored close to two hundred refereed journal and conference technical articles with more than thirteen thousand citations. He has been granted more than seventy U.S. and European patents and has served on numerous technical program panels and committees. In 2002, he co-founded Axiom Microdevices Inc. with two of his former graduate students, which mass produced and shipped more that 250 million units of world's first fully-integrated RF CMOS power amplifier.*

2. **Chris Valenta** (*Georgia Tech Research Institute*) Harvesting Wireless Power: Current Capabilities and Future Directions

   Abstract: This talk will address far-field, wireless power transfer systems used for solar powered satellites, internet-of-things applications, and RFID. An overview of the basic fundamentals of wireless power transfer will be presented followed by the current state-of-the-art energy-harvester efficiencies for UHF to microwave to millimeter wave systems. By focusing on the underlying physical principles of the harvesting mechanisms and taking advantage of unique semiconductor combinations, circuit configurations, and excitation waveform designs, it is possible to greatly enhance the RF-to-DC conversion efficiency of wireless power transfer systems - increasing their range, reliability, and effectiveness.

   ***Bio:** Christopher R. Valenta received the BS in ECE and OE from the Rose-Hulman Institute of Technology and the MS and PhD in ECE from the Georgia Institute of Technology where he pioneered work in microwave-energy harvesting using power-optimized waveforms. He is currently a research engineer, branch head, and Shackleford Fellow at the Georgia Tech Research Institute Electro-optical Systems Laboratory. Dr. Valenta is also the winner of the 2015 IEEE Microwave Magazine Best Paper Award.*

***SSP–S1 Technology Panel* 10:30am -12:00pm (Ali Hajimiri, Chris Valenta, John Mankins, Bong Wie)**

1. **John Mankins** (*President, Artemis Innovation Management Solutions LLC*) SPS-ALPHA: A Hyper-modular Approach to the Technology of Space Solar Power

***Bio:** John C. Mankins is a leader in systems innovation and management. He is President of Artemis Innovation Management Solutions LLC, founder of Mankins Space Technology, Inc., and former Chief Technologist for Human Exploration and Development of Space at NASA Headquarters in Washington, D.C. His 25-year career at NASA spanned flight projects and operations, including management of major advanced technology R&D programs. He holds undergraduate (Harvey Mudd College) and graduate (UCLA) degrees in Physics, and an MBA in Public Policy Analysis (Claremont Graduate University). He is a member of the International Academy of Astronautics and of the Sigma Xi Research Society.*

2. **Bong Wie** (*Iowa State University*) Orbit and Attitude Control Issues for Very Large Space Solar Power Satellites (SSPS)

Abstract: This talk presents an overview of various configurations of very large SSPS proposed during the past 20 years. In particular, attitude and orbit control system (AOCS) design issues in the presence various disturbance forces and torques will be discussed using a 1.2 GW Abacus platform in geostationary orbit that was once examined by NASA in late 1990s. A proposed AOCS architecture for a 1.2 GW (3.2 by 3.2 km) Abacus SSPS utilizes electric thrusters for integrated attitude and orbit eccentricity control by counteracting, simultaneously, attitude disturbance torques and a large orbital perturbing force. Significant control-structure interaction, possible for such a very large flexible structure, is avoided by employing a low-bandwidth attitude control system. However, a cyclic-disturbance accommodating control concept is utilized to provide proper attitude stabilization in the presence of dynamic modeling uncertainties and cyclic external disturbances. Other space systems engineering issues for launching and building very large SSPS in geostationary orbit will also be discussed.

Bio: *Bong Wie is the Vance Coffman Endowed Chair Professor of Aerospace Engineering at Iowa State University, Ames, Iowa. He received his B.S. in aerospace engineering from Seoul National University, and M.S. and Ph.D. in aeronautics and astronautics from Stanford University. Professor Wie's notable contributions in the fields of spacecraft guidance, control, and dynamics, including his seminal work on the control systems design for the International Space Station, have earned him high regard in the aerospace GN&C community. During the late 1990s, he was the PI of a research project for developing an AOCS architecture of NASA's Abacus SSPS. In 2006, the AIAA presented Dr. Wie with the Mechanics and Control of Flight Award for his innovative research on advanced control of complex spacecraft such as solar sails, large flexible structures, and agile imaging satellites equipped with control moment gyros. Since 2007, Dr. Wie has been establishing a unique research initiative program at Iowa State to develop innovative, yet practical, space technologies for mitigating the impact threat of hazardous asteroids or comets. In 2011-2014, he was a NIAC (NASA Advanced Innovative Concepts) Phase 1 & 2 Fellow for developing an innovative solution to NASA's near-Earth object (NEO) impact threat mitigation grand challenge and its flight validation mission design. His AIAA textbook Space Vehicle Dynamics and Control (2nd edition, 2008, 950 pages) is a classic in this field. He has published 180 conference papers, including 60 peer-reviewed journal articles. He has three patents on singularity-avoidance steering logic of control moment gyros. His second AIAA book titled "Space Vehicle Guidance, Control, and Astrodynamics" was published in August 2015.*

3. **Nobuyuki Kaya** (*Kobe University, Japan/Space Canada*) Recent Advances in Retro-directive Antenna for the Microwave Power Transmission for SSP

Bio: *Professor Nobuyuki Kaya, B.E.,M.E. and Ph.D., earned his degrees at Kyoto University. He is currently the Vice Dean of the Graduate School of Engineering at Kobe University in Japan. He held the position of Visiting Associate Professor of the Institute of Space and Astronautical Science. His areas of research include Space Solar Power (SSP), microwave power transmission and space observation of energetic particles. He has performed numerous space and ground demonstrations; in 2006 he and an international team from Japan and the European Space Agency successfully tested microwave beam control for an SPS using an ISAS sounding rocket and three daughter satellites deploying a large web: the "Furoshiki" experiment. He played a central role in the demonstration of key solar-powered wireless transmission as part of the Orbital Power Plant episode of the Project Earth television series on the Discovery Channel. Kaya is Vice President of a UN NGO, the SUNSAT Energy Council and is also Chair for Space Infrastructure in the International Astronautical Federation (IAF) Steering Committee and was Chair of the IAF Power Committee for six years.*

SSP – S2 Paper and Abstract **1:30 -3:00pm**

1. **Erinn van Wynsberghe, Paul Jaffe** (*McMaster University* and *Naval Research Lab*) High-Altitude Balloon for Wireless Power Transmission;

Abstract: The development of a geostationary, ultra-long duration high-altitude balloon could represent significant improvements for telecommunication and high-altitude observation services, offering greatly reduced cost, complexity, and risk compared to satellites, telecom towers, and unmanned aerial vehicles (UAVs or 'drones'). Advancement in this field is burdened, however by propulsion system energy requirements in excess of both solar power harnessing capabilities and battery storage mass limits. One solution is to deliver power wirelessly to the craft from a ground-based transmitter to operate the onboard propulsion system and facilitate long-term, uninterrupted missions. A lightweight superpressure balloon is proposed for deployment

to an altitude of 25 km. Electrohydrodynamic (EHD) thrusters are presented to overcome stratospheric winds and maintain position or guide the craft to a desired location. Energy can be provided remotely from a ground-based generator (devices such as a magnetron, klystron, etc.) and steered electrically with an antenna array (such as phased array, retrodirective array, etc.). A coherent electromagnetic wave at either 2.45 or 5.8 GHz is sent to a rectifying antenna ('rectenna') on the bottom of the balloon, where the wave is converted into direct current for onboard use. Mission architecture, energy requirements and safety concerns for a proposed system are presented along with recommended future work.

2. **Mingyu Lu** (*Western Virginia University*) Employing Phase-Conjugation Antenna Array to Beam Microwave Power from Satellite to Earth

3. **Mohsen Jamalabdollahi, Reza Zekavat** (*Michigan Tech*) Time and Frequency Synchronization for Space-based Solar Power Satellites Network via weighted OFDMA

4. **Paul Jaffe** (*Naval Research Lab*) Modular Space Solar Power Pathfinder Mission in Low Earth Orbit

Abstract: Since the 1960s, researchers and engineers have investigated the possibility of employing satellites to collect the sun's energy in space for transmission to earth for terrestrial consumption. This approach offers a way to overcome limitations of traditional ground-based solar associated with nighttime, clouds, and atmospheric losses. It also poses a unique opportunity for power to be provided nearly globally without existing grid infrastructure, a prospect that is attractive for military operations, disaster response scenarios, and developing countries. Significant challenges to the realization of the concept have historically included the high costs of space launch and spacecraft hardware, and the enormous scale of most proposed systems. For the most commonly posited wireless power transmission schemes, using microwaves below 9 GHz, there have been further stumbling blocks inherent to the physics of required aperture sizes for efficient transmission and in addressing regulatory issues. The modular space solar power pathfinder mission proposed herein endeavors to build off of recent technological advances and demonstrations to outline a technically feasible and economically attractive demonstration that would be a precursor to an operational space solar power system. This is accomplished by using the same or similar modular elements that would be used in the ultimate system, and by reducing costs and aperture size demands by residing in low earth orbit.

SSP–S3 Paper and Abstract **3:30 - 5:30pm**

1. **Gary Barnhard** (*Xtraordinary Innovative Space Partnerships, Inc. - XISP-Inc.*) Unbundling Space Power Systems to foster Space-to-Space Power Beaming Applications

Abstract: One path to hasten the development of viable SSP technology applications is through focused incremental technology development, which mitigates perceived cost, schedule, and technical risk associated with its use. This presentation will address one such possible focused effort -- the unbundling of space power systems (i.e., the separation of power generation, transmission, management, and loads).

Bio: *Gary Barnhard, President & CEO, Xtraordinary Innovative Space Partnerships, Inc., He is a Robotic Space Systems Engineer involved in the technical advocacy and development of space based solar power systems for space-to-space, space-to-alternate-surface, and/or space-to-space power beaming*

2. **Trevor Brown** (*Auburn University*) An Industry-Government Partnership for Space Solar Power
3. **Joshua Gigantino** (*Arizona State University*) Single Number Life Cycle Assessment of Space Solar Power
4. **Paul Jaffe** (*Naval Research Lab*) Review of Sandwich Conversion Modules for Space Solar Power
5. **Lewis Fraas** (*President JX Crystals Inc*) Self Pointing Mirrors for Solar Power from Space

Abstract: for SSP 2015: Solar cells have now entered the main stream for electric power production. By the end of 2015, world wide cumulative solar cell electric power installed capacity will exceed 200 GW. This has surprised the main stream energy community. This has been accomplished mainly by using silicon module technology with cell efficiencies of approximately 15%. There are now more opportunities and challenges with exciting potential solutions. One of the challenges that solar energy faces is associated with the fact that solar

energy is limited to daytime hours. A Space Power Satellite capable of providing solar electric power economically for 24 hours per day has been a dream for decades. Herein, an alternative will be described. A 10 km diameter constellation of mirror satellites in a sun synchronous orbit at an altitude of 1000 km deflecting sunbeams down to terrestrial solar power fields at dawn and dusk can provide 3 additional hours in the morning and another 3 additional hours in the evening. The key is that larger and larger terrestrial solar fields, photovoltaic or trough concentrated solar power, are already being built all around the world. Mirrors deflecting sunbeams down to earth is a much simpler concept. A surprising convergence of two technologies under development is now possible, i.e. lower cost access to space and the ongoing construction of larger and larger solar power fields. Further analysis of mirrors in space in a dawn dusk orbit combined with future solar power fields has shown this idea to be actually a potentially viable economical proposition [1, 2]. However, while this idea is very intriguing, the magnitude of its implementation is daunting. Nevertheless, the idea is intriguing enough to proceed with a first order design for the required mirror satellites. A mirror satellite development road-map will be presented here. It builds from mirror technology for solar sails as well as technology developed for the International Space Station. It appears that the technology is available to implement this mirror satellite design and at least go to a detailed design and test stage. If this concept is implemented in the future, the hours of solar electricity production in sunny PV fields around the world can be potentially increased to 14 hours per day with an increase in solar field capacity factor to 58% and a reduction in the cost of renewable pollution free solar electricity to below 6 cents per kWh. A first step in a development road-map could be the construction of a 20 m diameter space mirror to demonstrate full moon intensity illumination in Disney Parks in the evenings.

Bio: *Dr. Fraas has been active in the development of Solar Cells and Solar Electric Power Systems for space and terrestrial applications since 1975. In 1978, he published a pioneering paper proposing the InGaP/GaInAs/Ge triple junction solar cell predicting a cell terrestrial conversion efficiency of 40% at 300 suns concentration. He then led the research team at Boeing that demonstrated the first over 30% GaAs/GaSb tandem concentrator solar cell in 1989. He joined JX Crystals in 1993, where he has pioneered the development of various thermophotovoltaic (TPV) systems based on the GaSb infrared PV cell. Dr. Fraas holds degrees from Caltech, Harvard, and USC. He has written over 350 technical papers, over 60 patents, and two books. His most recent book is a Springer 2014 book entitled Low Cost Solar Electric Power.*

Tuesday Dec. 15 2015

IEEE WiSEE Plenary Talks: **8:30 – 10am**

***SSP–S4 Vehicle Launch Panel*: 10:30am-12:30pm (J. Olds, K. Hensen, E. Zapata, D. Bienhoff, G. Sowers)**

1. **Dallas Bienhoff** (*Boeing*) An Overview on RLV Development Programs

   Abstract: Spanning concepts from Saenger through Skylon, this discussion highlights conceptual and actual launch vehicle configurations, propellants, propulsion systems and projected payload capability. Partially and fully reusable concepts are addressed. The discussion concludes with the author's opinion on fully reusable launch vehicle payload limitations.

   Bio*: Dallas Bienhoff is Boeing's project manager for In-Space and Surface Systems in the Advanced Space Exploration Organization. He is responsible for capturing contracts and leading studies for NASA's Human Exploration & Operations and Space Technology Mission Directorates, commercial space companies, and Boeing. Dallas has over 41 years experience in space systems and human space exploration, of which 33 are in advanced projects organizations. His experience encompasses expendable and reusable Earth-to-Space systems, cislunar transportation architectures, cryogenic propellant depots, in situ resource utilization, space-based solar power, human space exploration mission concepts, lunar habitats, Space Station crew return vehicles, Space-Shuttle-derived launch vehicles, and Space Shuttle Main Engine development. Dallas has a MSE from California State University - Northridge and a BSME from Florida Institute of Technology.*

2. **John Olds** (*CEO, Space Works Enterprises Inc.*) A Review of Current and Future Launch Options for SSP

   Bio: *Dr. John Olds is the founder of SpaceWorks Enterprises, Inc. (SEI) and currently serves as the corporation's Chief Executive Officer. As CEO, Dr. Olds is responsible for the strategic growth and overall management of the company as*

well as establishing an integrating vision for the company's various operating divisions and technical activities. He also has ongoing technical roles within the company and holds a joint title as one of the firm's Principal Engineers. Dr. Olds has over 25 years of experience in the aerospace sector, including positions in private consulting, large aerospace industry, academia, and small business. Prior to founding SEI, Dr. Olds served as a professor in the School of Aerospace Engineering at Georgia Tech and Director of the school's Space Systems Design Lab. Previously, he was employed as an aerospace engineer with General Dynamics' Space Systems Division and later served as a Visiting Assistant Professor with N. C. State University's Mars Mission Research Center. In his professional and academic careers, Dr. Olds has been active in the field of advanced space transportation systems analysis and design with particular emphasis on the integration of automated software analyses using multidisciplinary analysis techniques. He is author or co-author of over 100 technical papers related to conceptual design of advanced space systems. He has led or participated in a wide range of aerospace concept design studies related to advanced launch systems, human exploration missions, LEO-based satellite constellations, lunar resource missions, space solar power satellites, and partially-reusable military spaceplane concepts. Dr. Olds has served as an industry advocate for affordable and responsive space access, human space exploration, high-speed point-to-point global transportation, and the expansion of commercial space business. Dr. Olds holds a Ph.D. in Aerospace Engineering from N.C. State University, an M.S. in Aeronautics and Astronautics from Stanford University, and a B.S. in Aerospace Engineering from N.C. State University. He has received both NASA TGIR and NASA Group Achievement awards for his participation in previous NASA space systems design projects. He is an Associate Fellow in the American Institute of Aeronautics and Astronautics and is a former Fellow of the NASA Institute for Advanced Concepts (NIAC).

3. **Edgar Zapata** (*Kennedy Space Center*) Emerging US Space Launch – Trends and SSP

Bio: *Mr. Zapata has worked with NASA at the Kennedy Space Center since 1988. He was born in New York City and studied in Puerto Rico where he earned a Bachelor's of Science Degree in Mechanical Engineering from the University of Puerto Rico. He is the recipient of numerous awards, for his work improving Space Shuttle operations processes and for his contributions to future space transportation systems studies, especially the introduction of the operations perspective into advanced projects. Publications and papers include authoring or co-authoring numerous papers on operations research and the path to affordable, routine space transportation that will one day open the space frontier. His recent work focuses on the development of analytical capability and life cycle models to analyze and improve space exploration architectures. Mr. Zapata looks forward to the day when access to space is safe, routine and affordable, having taken advantage of the experience and lessons of past and current space systems. During his time with NASA he has held the role of system engineer in the preparation and operation of Space Shuttle systems. These systems have included the Shuttle External Tank, the Shuttle cryogenic propellant loading systems/ liquid oxygen ground systems, and related systems. His operations experience has provided leadership in defining future reusable space transportation systems. These concepts have included single stage and multiple stage reusable rockets as well as very advanced air-breathing space-planes, spaceports and architectures. He has represented the Kennedy Space Center operations perspective in multitudes of agency level studies, working groups, analysis and strategic efforts.*

4. **Keith Hensen** (*L5 Society*) Solar Power Satellite Transportation Economics

Abstract: Electricity is a commodity. The primary way to gain market share with commodities is lower prices. Base load electrical energy from coal costs about 4 cents per kWh. Three cent per kWh power from space would be undercut coal by 25%. To reach that cost requires a capital investment of no more than $2400/kW ($12 B for a 5 GWe power satellite). This capital investment requires a transport cost to GEO of no more than $200/kg and a specific power of 6.5 kg/kW or less. This paper is an analysis of the transport cost and mass of a thermal type power satellite that may meet the target kg/kW. If we can meet these goals, then energy from space will undercut the cost of electrical energy from coal.

Bio*: Keith Henson, BSEE UofAZ 1969 was one of the L5 Society founders (1975). He has worked on power satellites off and on for 40 years, intensively since he retired. He has written widely on space engineering topics, such as vapor phase fabrication, large scale radiator designs, power satellites and space transportation systems, recently electric propulsion powered by microwaves. More at https://en.wikipedia.org/wiki/Keith_Henson*

5. **George Sowers** (*Vice President, Advanced Programs, United Launch Alliance*) Transportation Architecture for Cislunar space

***SSP-S5 Economy Panel*: 1:30 -3:00pm (Darel Preble, Gail Tverberg, John Mankins, Keith Hensen)**

1. **Darel Preble** (*Space Solar Power Institute*) Overview of Space Solar Power's antecedent Technical, Environmental, Economic and Energy Crunch;

Abstract: Adding Space Solar Power to the roster of renewable energy alternatives requires many technical, financial, and environmental prerequisites. The world has made no progress over the past 20 years in reducing the carbon content of its energy, instead CO2 levels are rising faster. Although Japan and China are working hard on bringing SSP to the global electric utility market, US energy policies continue to ignore the sleeping giant of SSP. Where are we in getting SSP initiated in the US? No US corporation has the patient financial resources, technology and charter to initiate an SSP industry. Just as the Comsat Act of 1962 created our robust commercial satellite communications industry, a Sunsat Act would create a commercial power satellite industry. We are hopeful that the next president and Congress will do so.

***BIO** - Darel Preble is President and Executive director of the volunteer educational non-profit Space Solar Power Institute, which he founded in 1997. From 1984 to1997 he was the Nuclear Security analyst and strategic planning analyst at the largest US electric power company. Darel authored three consecutive white papers on SSP for the aerospace and electric power industries in 1994, 1995, & 1996. He was general Chair, First Microwave Power Transfer Symposium, Georgia Tech, December 2011, co-chaired the IEEE RAST 2015, PIMRC 2014, and WiSEE 2013 and 2015 SSP Workshops. He chaired the Business Case Analyisis, of the landmark "Space-Based Solar Power As an Opportunity for Strategic Security", Report to the National Security Space Office, October, 2007.*

2. **John Mankins** (*Artemis Innovation Management Solutions LLC*) Realizing Economically and Programmatically Viable Space Solar Power
3. **Gail Tverberg** (*Space Solar Power Institute*) Energy Economics Outlook for Space Solar;

Abstract: Higher costs of energy production are becoming an increasing problem for the world economy. Increasingly, world commodity prices are falling behind these costs, indicating that the world economy cannot really afford today's high costs. These issues make it mandatory that the cost structure for Space Solar be low enough to significantly bring down the cost of energy production, not simply match the cost of other high-cost producers.

***Bio:** Gail Tverberg is Director of Energy Economics for Space Solar Power Institute, author of the popular blog OurFiniteWorld.com, and Fellow of the Casualty Actuarial Society. She uses her actuarial background to provide a unique perspective on energy and the economy.*

***IEEE WiSEE/SSP Funding Opportunity Panel:* 3:30 – 5pm**