Solar Power Satellites and the issues going forward after WiSEE 2015.

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December 14-16, 2015 was the bi-annual WiSEE conference on Wireless for Space and Extreme Environments, hosted by University of Central Florida in Orlando and the Institute of Electrical and Electronics Engineers (IEEE). WiSEE included tracks on Space Solar Power, passive wireless sensors and space internetworking. Here is a summary of ideas behind Solar Power Satellites and some of the issues that are holding up progress.

Solar Power Satellites (SPS) are a conceptual form of Space-Based Solar Power (SBSP or SSP) that collect sunlight, transform it into microwaves or lasers and transmit that energy to locations on Earth or in space that need electricity. The receiving equipment is surprisingly simple, building these systems creates jobs and technical skills, and the end product is the greenest form of electricity generation ever invented.

SPS has a dual effect on spaceflight economics that can open up development of the Inner Solar System; it requires many rocket launches driving per-flight costs down while being able to provide kilowatts to gigawatts for in-space receivers for propulsion and industrial use. While eventually providing unlimited green power for Earth, SPS enables our next steps out into the Solar System.

SPS is the only known form of power generation that can provide the entire world with abundant electricity while maintaining the heat balance of Earth's biosphere. SPS has an extremely low carbon footprint, less than 1/100th of terrestrial solar and around 1/10,000th that of combined cycle natural gas. Most currently proposed systems (by Mankins, Jaffe, Kaya) use gigahertz microwaves at 2.45 Ghz or 5.8 Ghz, 5.8 Ghz being nearly transparent to water, very important for heat balance.

Older SPS concepts typically involved massive metal space-frames covered in solar panels with mile-wide steerable transmitters, assembled by hundreds of astronauts. Modern concepts like Mankins' SPS-ALPHA use a composite sandwich structure module with amorphous thin-film photovoltaics above a direct current bus leading into a flat phased-array antennae across the bottom. The modules are launched in stacks on conventional rockets and can either self-point at a target or be docked together into a large flotilla of panels, orbiting in geosynchronous orbit (GEO). Together the phased-array antennae beam-form to create pulses that generate current in the receiving antennae or rectenna. Rectenna are typically a large metal mesh suspended above the ground. Higher density signals and smaller receivers are possible under this flexible schema that would provide point-to-point power for in-space transportation along with Earth-based industrial and military applications. Several safety measures are built in, the largest security issue is rectenna and ground transmission lines. Ranching or solar panel fields can utilize the land under the rectenna mesh.

Trained professionals — An issue that is directly related to the IEEE and workforce preparedness is that there are relatively few researchers actively working on what has until recently been an intractable problem. The basic techniques are well-established; the real issues in deploying SPS systems may be a workforce ready to finish developing and build these systems. The number of researchers with current demonstrations can be counted on one hand. People ready to design the circuits, structures, software and enterprises to operate these systems is lacking. Developing what are currently exotic microwave receivers for Earth and space is both a technical and political issue. Integrating these systems with existing rockets is likely the simplest part.

A cohort of engineers trained in this new type of space system, designers and managers able to synthesize the new requirements and policy specialists willing to tackle these issues are needed to make it viable.

Policy — The case for space solar power and SPS systems needs to be made convincingly to both the public and political institutions. This should happen through both grass-roots teaching using devices like Dr. Jaffe’s demonstrator and through coordinated moves to encourage sympathetic policies.

Making young professionals into effective voices for positive change is essential to this effort.

Technology readiness issues — Many elements of a functional SPS system are at middle Technology Readiness Levels, defined by NASA as TRL 1-9 with 1 being an observed phenomenon and 9 being off-the-shelf hardware. Jaffe has performed vacuum chamber tests at NRL on a complete SPS sandwich module. Marzwell has demonstrated an end-to-end analog system with solar photovoltaic collection providing electricity to a transmitter, received on another mountain in Hawaii. Dr. Kaya has performed multiple lab, public and suborbital rocket demonstrations.

Mankins estimates that it would take around 15 years to go from the current state of the art to flying a power-generating demonstrator (TRL 8) and an equal amount of time to scale up to a 5GW plant in geosynchronous orbit (TRL 9). Currently critical subsystems are stuck between TRL 4 and 6 and some have uncertainty about where to develop further.

New labs and startups with this new cohort of young professionals can drive these subsystems to higher readiness.

Transmission issues — There is a minimum strength power beam needed to trip the threshold voltage of a typical 20^km rectenna, or any receiving antenna. Ground tests between mountains by Marzwell and separate demos by Kaya and Jaffe show the principle works at smaller scales. Finding the right sizes of rectenna and beam characteristics is important, especially for in-space propulsion and mobile or smaller terrestrial applications such as a military forward operating bases or atop cargo container ships.

For stationary rectenna powering urban cores, much of the technology is fairly simple and can be located nearby on the ocean, desert or farmland. In that case the biggest transmission issues are communication interference from sidelobes and getting over the minimum transmission requirement. Inflatable or deployable rectenna with much higher beam density may be needed for in-space receiving.

Transmission issues are heavily dependent on system implementation and usage details that need to be further characterized as various SPS systems come online. Finding the right scales for in-space, limited/mobile terrestrial and baseline terrestrial beams is an avenue of currently needed research.

Financing & Business Development — The financial hurdle to fund a working SPS is mostly in funding the research & development and proving out the technology subsystems. The operational system can be earning money after the first launch and scales to literally out-of-this world markets.

An operable SPS system might be financed using commercial methods with a payoff time around 10 years after completion for sale of power to high-price markets. The goal is to achieve around $9 per installed kilowatt of capacity (2011 dollars) for a fully operational system. Some have argued that prototype units could be used for in-space propulsion to boost other client payloads but this is currently a small market.

While the payoff to electricity users (both industrial & residential) and to government (in taxes, military lives saved and new space colonies) is potentially quite large, the 15-40 year process of development toward those goals has proven daunting. Financing further technical readiness steps is also daunting as some of them involve spaceflight. NASA, JAXA and the Naval Research Lab have provided much of the previous funding due to the obvious potential but are neither mandated nor properly equipped to finance or run this type of project. Some kind of public-private partnership with loan and purchasing guarantees may be needed.

As SPS systems become viable, a business case must be made to current electricity providers, especially in coastal and desert regions. As with the development of wind and terrestrial solar, new construction sectors will need to evolve to build rectenna, ground transmission equipment and the factories to make thousands of these satellites. Development of one or several new companies will be needed.

Deeper modeling and trade studies are an opportunity to find the minimum viable products of this technology.

Orbits Utilized — The prospect of gigawatts of carbon- and heat- free power for terrestrial applications is compelling but comes at a cost. Most proposals for SPS systems place them in geostationary orbit (GEO), competing for orbital ‘slots’ with the proliferation of world telecommunications satellites. Orbital slots at GEO are precious, limited and nearly full.

Multi-kilometer structures with unique control dynamics may not be allowed based on telecommunication needs.

Options include placing telecom transmitters directly on an SPS, beaming power to new, larger telecom satellites or to operate in other orbits. Prototypes, in-space beaming and high-power applications may benefit from flying in a sun-synchronous 'high noon' polar orbit. Final system options include Medium Earth Orbit below the GPS constellations or halo orbits around Earth-Moon Lagrange points if GEO slots are unavailable.

Space-based solar power in general and SPS in particular have tremendous potential environmental, technical and industrial benefits, costs to users that could rival terrestrial power sources, provide world energy security and fast in-space propulsion. SPS can be an enabling technology for lowering rocket launch and spaceflight costs. Convincing the US and international community's citizens, regulators and politicians of this utility will require hard work and dedication among a new cohort of professionals who can practice an integrated approach to engineering these new systems.

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Joshua Gigantino is a designer, entrepreneur and technologist focused on applying industrial design research techniques to high technology fields and applying high technology practices to other fields. He holds a BFA and MSD while in PhD study at Arizona State University's School of Arts, Media & Engineering, and is currently developing a FabLab in Tempe, Arizona. He recently published *Single Number Life Cycle Assessment of Space Based Solar Power.*