Spacetenna Flatness and Error Correction

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***Abstract*—Wireless Power Transfer (WPT) from space-to-earth at a large scale will not be possible until the Side Lobe Levels (SLL) are reduced many orders of magnitude from the current technology available today. To accomplish this, careful design of the transmitting antenna (spacetenna) is imperative. Any module failures or errors in connectivity, including askew angles between adjacent sandwich modules, reduce the effectiveness of the antenna design and thereby increase SLL. This work examines two interrelated issues; error detection and repair, and spacetenna flatness correction. Multiple different designs of sandwich module mechanical connections, wiring, and control are examined. The results of the analysis and best options are presented in order to facilitate for ultra-low SLL for use in Space Solar Power for the benefit of humanity and the environment.**

***Index Terms*— wireless power transfer, sidelobe levels, space solar power, desense.**

I. Introduction

OFF-AXIS energy from a space-to-earth power beam will desensitize radios, Wi-fi, Bluetooth, and other wireless services, compromising their performance for a wide radius on the ground. The transmit antenna from an orbital powersat, called a "spacetenna" is a regular array of individual radio frequency (rf) antenna elements which are fed with a sinusoidal power input, each having a phase delay such that the elements work in synchrony, and minimize off-axis energy through destructive electromagnetic interference. The off-axis energy forms in a rippling pattern radially outward from the beam axis, at an angle to the main lobe of the ripple, which is directed at the center of a receiving antenna, called a "rectenna", or a "receivarray". The peaks of such off-axis ripples are called sidelobes, and until recently the lowest value reported for sidelobe power relative to the main lobe was –60dB, or a reduction of 1,000,000. For many space solar power architectures, a geostationary earth orbit (GEO) powersat will deliver about five gigawatts (5E9 W) of power. Sidelobes at –60 dB will still have multi-kilowatt power levels, which is larger than cellular towers which broadcast with 100 to 500 W of power, and enormous relative to individual two-way radios and cell phones. Such overwhelming power levels need not be at the same broadcast frequency to cause sensitive receivers to become overwhelmed. This effect is called desensitization, or "desense" by rf practitioners. In the field of electronic warfare, it is called "jamming." For wireless power transfer (WPT) from a GEO spacetenna to a terrestrial receivarray it is absolutely essential to have much lower sidelobes.

In 2016 one of the authors published a study which discovered that a triangular array of antenna elements within a hexagonal grid, and which is built sufficiently large, can produce sidelobes as low as –240 dB[1]. A published report from 2015 identified the sidelobe level (SLL) needed for a 5 GW powersat to avoid desense of terrestrial wireless communication standards, and this threshold is about –82 dB[2]. It would seem a solution is at hand. Consider though, that with millions of antenna elements on a spacetenna there are nearly as many power amplifiers and phase shifters, sensitive rf electronics which have non-zero failure rates. As the fraction of failed elements increase, the actual SLL will worsen, such that a –240 dB design must have fewer than 6600 failures at any given time to maintain SLL below the –82 dB threshold. This paper studies this matter in some detail and presents solutions to it.

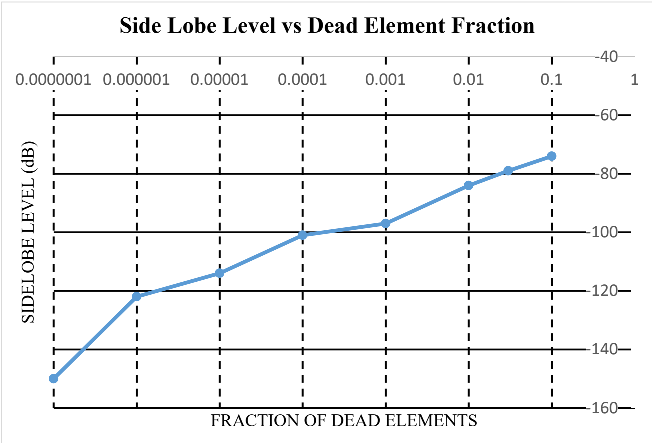

Figure **1**. Loss of side lobe level reduction relative to main lobe versus fraction of dead elements randomly located[12].

A second non-ideality of the spacetenna is deviation from a planar structure. Large structures in orbit are subject to gravity perturbations from many sources, such as the orientation of the sun and the passing of the moon, both of which drive tides on earth's seas. Solar wind exerts pressure on such a large structure, and any mechanical force, from construction to docking of repair spacecraft, can introduce membrane vibrations. This is true regardless of how stiff any potential support structure can be made. Coming to the rescue of this problem is the ability to modulate the phase angle delivered to each element. If the non-planarity of the spacetenna can be determined precisely (to within a small fraction of a wavelength) at each location, then in theory these effects can be ameliorated. In practical application, this is a significant challenge. For the current work we assume there is some means

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by which the large- scale deviations of the spacetenna can be monitored and corrected for, but only if small-scale deviations are sufficiently small. In particular, for a modular design, which facilitates repair of failed elements as noted above, it is important that replaced modules align squarely with their neighbors, with a minimal askew angle. And with the requirement to keep the number of failed elements to a minimum, it is further important to quickly swap out a bad module for a good one. This paper explores means by which modules can be replaced quickly and easily, and which also maintain planarity with neighboring modules.

Interwoven with concerns for error detection, module repair, and local flatness is the means by which control signals are managed across the spacetenna. A formal analysis using the method of Failure Modes and Effects Analysis (FMEA) identifies and ranks possible hazards which can arise in the operation of a high power spacetenna. Considerations of operational performance and safety, as well as maintenance of low SLL, affect the architecture of control across a large spacetenna. These factors are studied in more detail using the methodology explained next, and with results reported on the findings. In the Discussion section the authors relate these outcomes to the design and operation of space solar power spacetennae which address the potential “show stopper” of high SLL.

II. Methods

The objective of the system is to transfer a constant power with an acceptable range of SLL. We are looking to lower down the SLL to -82 dB as discussed in McSpadden’s paper which is the SLL amplitude which does not interfere with the operation of Wi-Fi, Bluetooth and emergency radios[2]. System requirements are developed in order to meet this objective and it is shown in Table 1.

Elements	Requirements	
Side lobe levels (SLL)	Shall	be lower than -82 dB which is good for Wi-Fi, Bluetooth and emergency radio.
Power transfer	Shall	be constant with absolute accuracy of the beam over long distances.
Error Detection	Shall	be able to detect more than 6600 (0.3% of 2.2millions) broken modules
	Should	be reliable, non-invasive, fast, accurate.
Repair Robots	Shall	be fast and accurate
Control Method	Shall	be able to turn off the spacetenna by seconds (fast). Kill switch shall be investigated and be operable by utility company or community leaders.
	Shall	be able to control x, y, z, theta, and phi directions of phase arrays with thresholds for acceptable movement of modules.
	Should	minimize the number of components, complexity of wiring connection and information delay
Connection method	Shall	be making sure the askew angle between adjacent module is in the range of 0.1 degree (P. Schubert, IAC-16.C3.2.3 Sidelobe Reduction For Geo To Earth Wireless Power Transfer) and connection is stable.
	Shall	be making sure the speed of connection is fast and the connection is strong.
	Shall	be able to connect all the modules electrically
Security	Shall	be resistant to all sorts of system hackings.
Environmental impact	Shall	be minimal (not bringing devastating disaster)

Table 1. System requirements

A paper published by Dr. Schubert has shown the breakthrough in SLL that made our objective possible. Arrays of modules shall be arranged in hexagonal perimeter with 950m of diameter[1]. Random failures of modules are studied, and its parameters is restricted based on factor of safety. 0.3% of random failure rate is determined in our design and it will be the controlling factor for error detection. Repair robots shall be able to replace the defective modules fast enough to maintain the sustainability of system. Control methods of the system should be taken into consideration in the design to make sure that it is safe to be operated and react to the potential problems arise. Phase arrays shall be able to be turned off or adjusted. Connection between adjacent modules are important in making sure the askew angle between adjacent module is acceptable for the SLL and efficient in capturing the sunlight. Resiliency against hacking would also be necessary to ensure the safety of the equipment and surrounding area. An additional consideration is the necessity for absolute accuracy of the beam transferred over long distance to prevent health or environmental concerns from the surrounding community. FMEA is determined and used in our system design to further refine our design structure. A kill switch or similar operational device is necessary to be implemented to prevent damage due to high SLL.

III. Design Options

A. *Module Connection*

Description of methods to ensure spacetenna flatness, including different connection types and the analysis of them.

Four different designs for connecting modules were drafted in order to ensure spacetenna flatness as well as easy removal for module repair. Eight different criteria were also created in order to qualify each design and to gain an indication towards the best design.

The first design is one that was inspired by how railroad cars attach to each other. The design uses a pin and a latch which are fixed by a rotating screw with the pin on one module and the latch on the other. Once they catch and as the screws twist into the respective modules the modules are pulled and locked together.

The second design uses a male and a female port on either sandwich module that want to connect to each other. Once the male port is inserted into the female port tabs can be released from the male port into slots in the female port. This "flying tab" design locks the modules together. The tabs would be spring loaded and could be controlled by a screw mechanism. Retraction requires a winding action from a rotating end effector, and deployment is by depressing the latch on a release ratchet.

The third design is inspired by how binder clips work and uses a series of alternating clip and wire connections. The wire connections are rigid and work in compression where the clip connections are in tension by springs attached inside the sandwich module. This alternation of tension and compression creates a strong bond between the modules.

Finally, the fourth design is inspired by how mechanical puppet hands work. One sandwich module has a mechanical hand/finger that curls as pressure is placed against its palm. Therefore, as that module comes in contact with another that has a rod as the rod puts pressure on the palm the hand curls and grabs the rod creating a connection between the modules.

These four designs were then scored on different criteria on a 1-3-9 scale. The criteria used were (from highest weight to lowest); registration (how little give the connection has) with a weight of 9, connection speed (the speed at which a module could be placed/removed from the spacetenna array) with a weight of 9, stability in all axes with a weight of 9, electrical connection (how well the connection method facilitated an electrical conduit) with a weight of 3, robot simplicity (how simple it is for a repair robot to replace a module with this connection) with a weight of 3, mechanism simplicity, rubbing metal (how much metal to metal friction would cause damage as well as dust) with a weight of 3, brittle metal (how much metal could become brittle) with a weight of 1. By multiplying the weights of each criteria against the individual scores an overall score for each connection design could be calculated. The highest scoring designs were the binder clip method and the flying tab which both scored 184.

B. Error Detection and Repair

4 different types of error detection methods are developed in order to meet the objective of 0.3% of random failure rate. Characteristics including reliability, invasiveness, accuracy, cost, speed and complexity are used in comparing all 4 methods with different weight assigned to each characteristic. Invasiveness is the measure of how bad it could be affecting the performance of system in term of power transferring.

First and foremost, the coordinate system can be used by connecting all the sandwich module electrically within a grid. Each module will have its position in x and y axis, thus if there is anything wrong with the electrical connection, we can track back to the original position of faulty module and replace it immediately. Second, we can also use robots that have been built to replace the faulty module to test on the operation of each module. This method, however, might cause an increase of invasiveness to the performance of system and the speed of checking the module is comparatively slower than other methods. Third, couple inductance technology can be built in the detection system as well. Since all the modules are connected among each other, it is possible to cover each and every single module that is involved in the system. Last but not least, we can also observe the graph generated by rectenna on Earth on the performance of power transferring and the measurement of SLL. This reverse simulation would be effective in tracking the problems arise in the system.

By using a similar scoring method as was used for connection methods the error detection methods could also be scored. The criteria used were reliability with a weight of 9, non-invasiveness with a weight of 9, accuracy with a weight of 9, cost with a weight of 3, speed with a weight of 3, and complexity with a weight of 1. The highest scoring method was the robot checking modules approach with a score of 192.

C. Control Methods

Control method of the system will deeply affect the operation of system. Phase of the beam is the main concern in designing the control method for the system. It is highly related to the performance of SLL. The leading or lagging phase of the beam will cause an increase in SLL. The two control methods that have been studied is centralized control and distributed control.

Centralized control requires a "master brain" to connect all modules to manipulate the phase of the system. In order to achieve that, wiring components for each sandwich module will be increased and complexity of electrical connection in the system will be increased exponentially. Distributed control requires an automated system in each single module to adjust the phase of the system. This criterion will lead to more equipment used on each individual sandwich and contribute to the complexity of phase control.

IV. Results

Because low SLL has only been shown for triangular element arrangements, the logical shape of a sandwich module is an equilateral triangle containing antenna elements in multiples of three. With an ISM band transmission frequency associated with a 122 mm wavelength, the gap between sandwich modules can be 40 mm. Figure 2 shows a computer aided design of a three- element module having six flying tab connections.

The flying tab design includes an arcuate, conductive surface on the male portion, which serves a dual role. First, the friction interference draws adjacent modules together intimately, with no mechanical slop, thereby serving the role of local flatness. Second, this intimate connection provides redundant electrical links through which addressed communications protocols can deliver critical information, such as: (a) long-range flatness deviation, and (b) kill switch shut down signal.

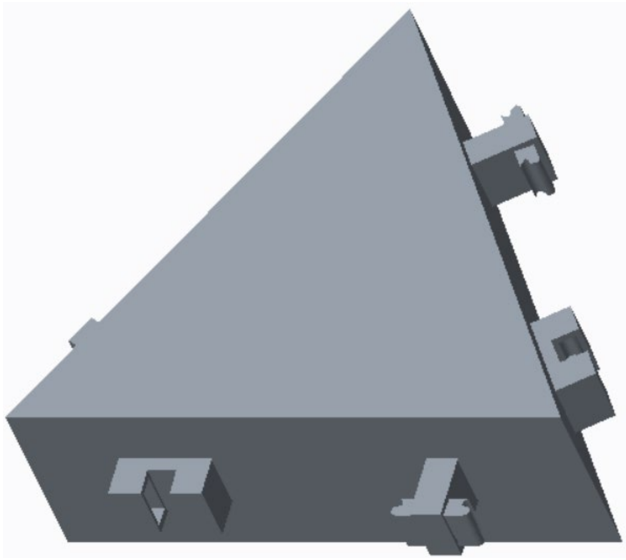

Figure **2**. Triangular sandwich module showing flying tab connection method (second option, section III.A).

Since the robot checking module approach was the most favorable option based on the scoring methods employed it was then simulated in a program written in MATLAB to test its feasibility. The simulation accepts parameters of the diameter of the spacetenna, the percentage of sandwich modules expected to fail each Earth day, the number of antenna components in each sandwich module, the number of available robots, the time necessary for a robot to replace a sandwich module, the time necessary to retrieve a new sandwich module, and the traversal speed of the robots.

In the simulation each robot follows a prescribed closed loop path over an assigned region of the spacetenna. These regions have an approximately equal amount of sandwich modules and do not have a specified geometry on the array. It was assumed that the geometry of the closed path patrol loops of each robot is independent to their respective performance in error detection.

Before the main loop of the simulation the time scale is determined with each unit of time being equal to one tick (one increment). By assuming the spacetenna is a regular hexagon and by using the number of antenna components per sandwich module to calculate the number of sandwich modules the size of each sandwich module is determined. The simulation uses the size of each sandwich modules and the traversal speed of the robots to determine the length of one tick of the simulation, which is equal to the amount of time in seconds it takes for a robot to move from the center of one sandwich module to the center of another.

At the beginning of the main loop of the simulation a random number of failures is generated according to a Poisson distribution whose parameter is equal to the product of the fraction of sandwich modules expected to fail in one day and the total number of sandwich modules, this value is then divided by the number of ticks in one day. Once the failures are generated, they are randomly assigned to locations on the spacetenna, however they will not be assigned to a position that already has a failure or is already occupied by a robot. After failures have been distributed the robots move to the next sandwich module on their path. If a robot finds a broken module they are immediately put into a queue where they begin the process of repairing the module and then resupplying. It was assumed that the repair time and the resupply time could be modelled as static values independent of the condition of the module being repaired or the location of the robot on the array. If a robot has finished resupplying it resumes its path on the spacetenna. At the end of one tick of the simulation data is collected and stored about the current number of module failures, the detected number of module failures, the total number of inactive modules (as a result of modules failing as well as modules rendered inactive due to having a robot passing over them). The simulation also tracks the activity of the robots logging how many are reloading, currently repairing, or scanning for broken modules.

Figure 3 shows the output of the simulation where there was one antenna component in each sandwich module, 0.1% of sandwich modules were expected to fail each day, the robots moved at 0.5 ms^{-1}, repair time was five minutes, reload time was 40 minutes, number of available robots was 250, and the number of antenna components was 2.2×10^6 spaced over a 950m diameter array. The simulation spans a period of time of a week.

Since all the variable values apart from the number of antenna components and the diameter of the array were educated guesses graphs like Figure 3 were used mainly to gain an understanding of the patterns and behaviors of the system. The most important of which being that the system (across a series of multiple simulations) often reaches a steady state. Precisely, the majority of simulations that were run reached a steady state at some point (the length of initial transients varied), however some simulations which were run with a high expected failure rate or a very low number of available robots saw an increasing number of inactive antenna components with apparently no steady state reached.

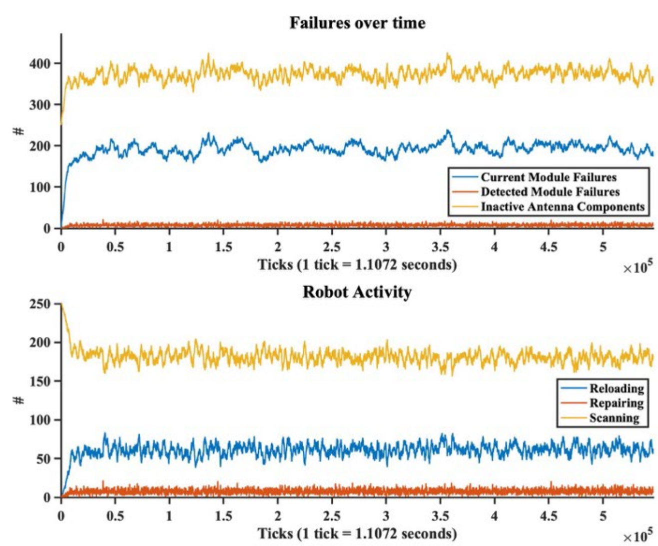

Figure **3**. Graph of failures over time and robot activity over a simulation period of a week. Demonstrating general behavior of simulation.

To gain a better understanding of how these variables interacted with each other and to establish a series of design guidelines for safe operation the effect of number of antenna components per sandwich module, number of available robots, and expected failure rate on mean number of inactive components were systematically investigated.

First, a series of simulations were run with a varying number of antenna components per module (1-9) and available robots (50-300). Each simulation was run over a period of a month and the mean number of inactive components over the last six days were measured as the output. These simulations were also run with a fixed expected failure rate of 0.1% of sandwich modules each day. The results of this are shown in Figure 4.

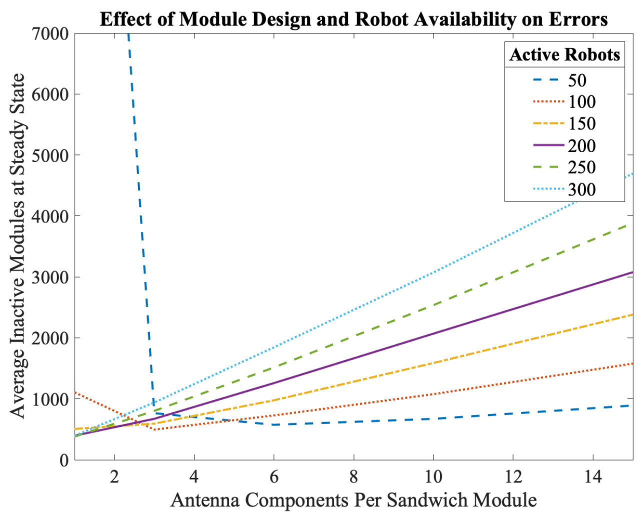

Figure **4**. Graph of the effect of the number of components per sandwich module and the number of available robots on mean inactive components.

Figure 4 suggests that it is advantageous to opt for a high number of antenna components per sandwich module. However, the limitation to this is that by using a higher number of antenna components per sandwich module the individual size of sandwich modules increases, which increases the diameter of the necessary transport fairing for transporting the modules to space. A sandwich module with 9 antenna components with spacing for 2.45GHz transmission (950m diameter spacetenna) has a diameter of approximately 1.6m.

Second, the effect of failure rate itself on mean inactive modules was measured in the same fashion as was done with number of antenna components per sandwich module. The results of this are shown in in Figure 5.

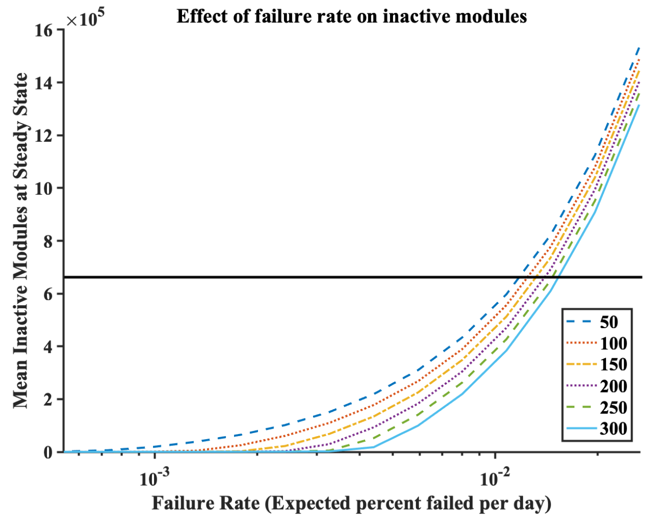

Figure **5.** Graph of the effect of failure rate on mean inactive modules as a function of number of robots for a 950 m spacetenna, at steady state. A horizontal black bar has been which intercepts the vertical axis at 6600, the upper safe limit for concurrent inactive modules.

As shown in Figure 5 the system becomes increasingly sensitive to changes in the failure rate beyond roughly 0.001. This also implies that at higher failure rates the system is more susceptible to catastrophic failure where the number of inactive modules continually increases and never reaches a steady state before the safe limit of inactive modules, which was measured to be 6600 based off the limit of 0.3% failure at any time.

The results from these simulations suggest that if the sandwich modules could be engineered to have an expected failure rate of less than 1% reaching a steady state of far less than 6600 inactive modules is very achievable by using a robot patrol error detection method.

V. Discussion

There are many requirements for a system of this size and impact. One requirement is a kill switch, operable by utility, company, and community leaders, which would prevent damage due to high SLL if necessary. A control system to operate the modules and a resiliency against hacking would also be necessary to ensure the safety of the equipment and the surrounding area. This requirement has no impact on the connection or error detection methods, although it does require external SLL sensors in order to shut down the equipment if this is out of range. Additionally, although either control method would work, there needs to be a distinguishable (non-hackable) retrodirective beam that can communicate through amplitude modulation with the distributed or centralized control software in order to turn off the beam if necessary.

Another high priority requirement is the delivery of constant power with low side lobe levels, as previously mentioned. This requires the sandwich modules to have connections that allow for control in the x, y, z, theta, and phi directions, with thresholds for acceptable movement of modules to ensure spacetenna flatness. This requirement is a high-priority distinguishing factor between the different types of module connections presented. Additionally, the necessity of low side lobe levels requires a certain percentage of modules to be completely operational, which limits the number of failed modules along with the amount of repairing robots allowed on the spacetenna at any time.

This system also has the requirement of an operational area on the ground that is as small and has as little environmental impact as possible. The area of the rectenna is directly related to the frequency of the beam; if the beam frequency is higher, then the rectenna area can be smaller. Unfortunately, that also requires the spacing of the antenna elements on the spacetenna to be smaller, which could affect the area available for the connection of different sandwich module elements, and the size of the repairing robots, which in turn could affect repair time. These are all considerations that need to be taken in to account in the final design.

An additional consideration to bear in mind is the necessity for absolute accuracy of the beam over long distances to prevent health or environmental concerns from the surrounding community. To accomplish this, there must be a control system that allows for an extremely accurate phased array antenna. If centralized control is used, the retrodirective beam would indicate the appropriate phase delay of each module in response to a master timer, which itself must account for signal delay across the large antenna surface. If distributed control is used, there must be 3+ retrodirective beams with intermittent energy pulses to triangulate the distance and thereby the phase delay required by each module. The increase in number of retrodirective beams would also increase the resilience of the system to hacking, as the kill switch or other important information would be encoded in all beams and therefore would be much more difficult to fake.

VI. Conclusions

The results of the analysis of both the spacetenna flatness and the error correction, including the chosen method to solve both problems, and the control architecture selected provide a means to achieve the requirements for the spacetenna. Detailed simulations conducted on the process of detecting errors with roving repair robots, each of which carrying a single replacement, showed that the number of such robots is modest, and even with their shadows occluding portions of the spacetenna arrays their presence does not, by itself, jeopardize the low sidelobe level needed to overcome the showstopper of GEO to earth wireless power transfer. Repair robots retrieve fresh sandwich modules at the periphery of the spacetenna and have been shown to respond within one day to a localized disaster such as the crash of an errant spacecraft. A detailed design and method of operation for attaching adjacent sandwich modules, each triangular in shape, is shown to optimize the local flatness of the spacetenna. The flying tab method is easily adapted to spider-like repair robots which can rapidly engage or disengage each tab with a single proboscis having a rotating end effector. In this way, a repair robot can traverse either the solar panel side or the phased array antenna side of the spacetenna to swap out failed sandwich modules which it detected during its traverse. The Ohmic contact which is facile with a flying tab attachment mechanism provides for wired communication within the plane of the modular spacetenna, such that all modules can be shut down as may be needed. Formal analysis using failure modes and effects analysis (FMEA) identified the need for a kill switch to be essential to spacetenna design. Because a sandwich module design does not permit a separate superstructure, to avoid shadowing or interference, such a centralized method of control, combined with a flying tab attachment mechanism activated by spider-like repair robots has been shown an effective and robust method for spacetenna maintenance and operation.

References

[1] Schubert, P.J., , “Sidelobe Reduction for GEO to Earth Wireless Power Transfer,” Int’l. Astro. Conf. 2016, Guadalajara, Jalisco, Mexico, 26-29 Sept 2016.

[2] McSpadden, J., “Solar Power Satellite Technology and Frequency Selection,” IEEE Wireless Power Transfer Conference 2015, Boulder, CO, 13-15 May 2015.