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The Lightweight Integrated Solar Array and Transceiver (LISA-T): second generation advancements and the future of SmallSat power generation

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ABSTRACT

This paper describes the second generation advancements of the Lightweight Integrated Solar Array and Transceiver (LISA-T) currently being developed at NASA's Marshall Space Flight Center. LISA-T is a launch stowed, orbit deployed array on which thin-film photovoltaic and antenna elements are embedded. Inherently, small satellites are limited in surface area, volume, and mass allocation; driving competition between power, communications, and GN&C (guidance navigation and control) subsystems. This restricts payload capability and limits the value of these low-cost satellites. LISA-T is addressing this issue, deploying large-area arrays from a reduced volume and mass envelope – greatly enhancing power generation and communications capabilities of small spacecraft. A matrix of options are in development, including planar (pointed) and omnidirectional (non-pointed) arrays. The former is seeking the highest performance possible while the latter is seeking GN&C simplicity. In both cases, power generation ranges from tens of watts to several hundred with an expected specific power >250W/kg and a stowed power density >200kW/m^3. Options for leveraging both high performance, 'typical cost' triple junction thin-film solar cells as well as moderate performance, low cost cells are being developed. Alongside, both UHF (ultra high frequency) and S-band antennas are being integrated into the array to move their space claim away from the spacecraft and open the door for omnidirectional communications and electronically steered phase arrays.

INTRODUCTION AND MOTIVATION

Satellite miniaturization continues to open the door to space, enabling lower cost solutions to the traditional large-scale satellite. However, the capabilities of these *small spacecraft* are largely constrained. Inherently, these satellites have very limited surface area, internal volume, and mass allocation available. This drives competition between important subsystems such as power generation, communications, and the payload itself. Within this competition a clear theme has emerged: more capability in small spacecraft requires more electrical power generation. Though current solar array technologies are capable of the required power, there is no area, volume, or mass allocation to accommodate. This drives the need for advanced power generation concepts.

An important class of small spacecraft is known as the Cubesate, a satellite built to standard dimensions (Units or 'U') of 10x10x11cm. They can be multiple U's in size (1U, 6U, 12U, etc.) and typically weigh less than 1.33kg per U. As with large scale satellites, Cubesat solar arrays can be divided into two main categories: body mounted and deployable. Body mounted arrays are clearly limited by sparse Cubesat surface area, with a typical 3U body mounted panel producing around 7W peak BOL (beginning of life) power. These panels can be mounted on all exterior faces of the satellite, creating 2-axes of 7W generation; somewhat relaxing the requirement of pointing a single panel at the sun. To increase power generation, several deployable options exist. 3U, 6U and 12U array designs, which increase power to 35-80W, are currently available. Table 1 summarizes some sate of the art (SOA) Cubesat array designs. Both SOA body mounted and deployable designs typically comprise thick film gallium arsenide (or silicon) based solar cells, covered with a radiation stable glass and mounted on an FR-4 or similar laminate printed circuit board. This creates a reliable and robust array; however, to achieve higher power generation levels without increasing area, volume, and mass allocation, these materials and their supporting deployment mechanisms must be adapted. Emerging thin-film solar cells, lightweight polyimides, and compact deployment mechanisms represent an opportunity to do just that.

Table 1: Summary of SOA Cubesat solar arrays (values estimated from publically available data)

	Generation Axes	BOL Power (W)	Stowed Power (kW/m^3)	Specific Power (W/kg)
Clyde Space 3U Body Mounted	2-axes	7.3	~33	~53
MMA HaWK	1-axis	36	~99	~130
Clyde Space 3U Deployable	1-axis	29.2		~54
Tethers Unlimited Sunmill	1-axis	80	~83	~53
Pumpkin turkey Tail	1-axis	56	~142	~89
NASA iSAT (2016 design)	1-axis	72	~45	~58
LISA-T Pointed*	1-axis	>200	>200	>250
LISA-T Non-pointed*	3-axes	>50	>50	>50

*Note: both options can use either a lower cost, lower performing or higher cost, higher performing solar cell. The pointed panel was assumed to use high performance, while non-pointed calculated using the low cost cell. See text for more information.

The use of thin-film based solar arrays for spacecraft applications has long been recognized as an advantageous power generation option.[1] Thinner materials yield a mass savings, equating to lighter launch loads and/or more payload allocation. Perhaps more importantly for the small spacecraft community, their mechanical flexibility lends itself well to stowage and deployment schemes, allowing an improvement to both specific power (W/kg) as well as stowed power density (W/m^3). Furthermore, marrying solar generation and communication capability on the same deployable is known to be an advantageous configuration, reducing space claim and mass, while creating opportunity for higher gain design, omnidirectional communications, and electronically steered arrays. These benefits make thin-film arrays an exciting prospect for small-scale satellites. Though several larger scale arrays are in development, sub-kilowatt thin-film arrays remain scarce. Marshall Space Flight Center's (MSFC) Lightweight Integrated Solar Array and Transceiver (LISA-T) is addressing this, deploying large-area thin-film arrays from a reduced volume and mass envelope – greatly enhancing power generation and communications capabilities in small spacecraft.

LISA-T is a launch stowed, orbit deployed array on which thin-film photovoltaic and antenna elements are embedded. The technology can be likened to smaller-scale solar sail, with photovoltaic cells, antennas and electrical wiring – all thinner than a human hair – built into the surface. LISA-T builds upon previously published concepts, such as the PowerSphere, Inflatable Torus Solar Array Technology (ITSAT) and others. The project is leveraging advancements in the solar sail community, the photovoltaic community as well as innovative materials and deployment advancements from both government and industry. A matrix of array options are under development to adapt LISA-T to different mission needs. Both a planar (pointed) and omnidirectional (non-pointed) array are being designed. The former is seeking the highest performance parameters possible, while the latter is seeking 3-axes of power generation; greatly simplifying GN&C. Power generation ranging from tens of watts to several hundred with a specific power as high as >250W/kg and a stowed power density >200kW/m^3 is being targeted. Table 1 summarizes the LISA-T targets for both configurations. Options for leveraging both a high performance, triple junction thin-film solar cell as well as a low cost single junction are being developed. Different antenna designs, including UHF (ultra high frequency) dipole, S\X-band helical, and S\X-band patches, are being incorporated. Herein, the generation II advancements of the LISA-T platform are discussed.

BASIC SYSTEM OVERVIEW

Figure 1 shows a conceptual rendering of both the non-pointed and pointed LISA-T arrays.

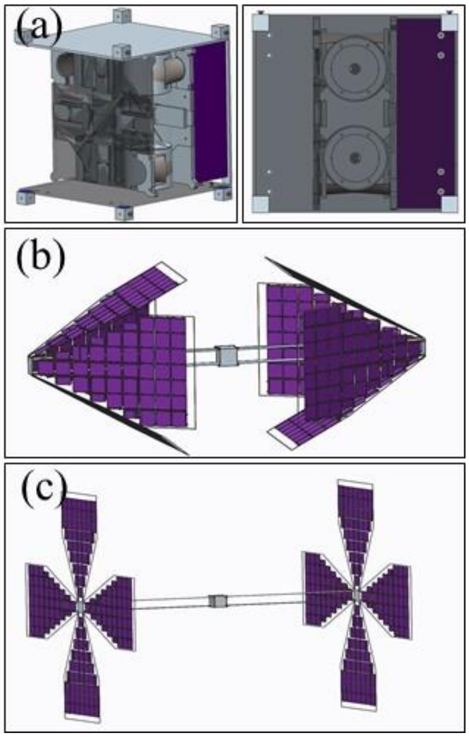

Figure 1: Conceptual rendering of LISA-T. (a) Stowed, (b) central boom deployed, (c) non-pointed deployed and (d) pointed deployed.

For both panel options, a central boom structure first deploys a base plate out either side of the satellite. Z-folded and/or rolled petals (panel assemblies of substrate, solar cells, covers and electrical traces) are then opened from the deployed plates to form either a structured three-dimensional or planar array. Embedded solar cells and antenna elements on the three-dimensional configuration create omnidirectional power generation and communication ability, levying no requirement of spacecraft pointing. With the planar configuration, the power generators and antennas must be pointed, but the use of stowed volume and mass allocations are optimized. In both configurations, a 1U stow is being targeted for modulatory and integration simplicity. However, each deployed wing is designed as its own inclusive unit and could be separated to accommodate a >6U satellite where double-side deployment from a single U is not feasible.

Work to date has brought the non-pointed option to technology readiness level (TRL) 4 and the pointed to TRL5. Current funding efforts are to bring both configurations to TRL6 by the end of calendar 2016. Details as to the current generation of materials, deployment mechanisms and electronic components are discussed in subsequent sections.

MATERIALS DEVELOPMENT

At the base of LISA-T are a handful of lightweight, thin-film materials which fold and stow compactly, but are mechanically tough enough to withstand deployment forces and robust enough to survive in the space environment. Generation I prototypes comprised uncovered photovoltaics (PVs) bonded to a ~25µm Kapton HN (DuPont, U.S.A.) substrate *via* a low outgassing pressure sensitive adhesive. Though this represented a significant improvement to volume and mass requirements as compared to current SOA assemblies, folding remained somewhat bulky and there was risk of adhesive creep during stowage and tear propagation during deployment. Furthermore, light scratching on the PV surface, resulting from the unfolding process during deployment, as well as the need to protect the cells from both pre-lunch (e.g. humidity) and space (e.g. atomic oxygen) environments, has prompted the need for a thin-film, integral PV cover.

Second generation assemblies (Figure 2) have been fabricated from covered PVs bonded to a ~3µm toughened colorless polyimide 1 (TCP1) (NeXolve, U.S.A.) substrate *via* an adhesive-less joining method. Figure 2b-e shows two generation II material assemblies as well as a comparison of adhesive and adhesive-less bonding. Figure 2b used a low cost (~$20/W), moderate performance (9-11% power conversion efficiency (PCE) at air mass 0 (AM0)) copper indium gallium (di)selenide (CIGS) (Ascent Solar Technologies Inc., U.S.A.) cell. Though this cell is being produced for terrestrial applications, early indications show good potential for use of these lower cost generation II assemblies in low Earth orbit (LEO) missions. Figure 2c represents a higher performance option and used a typical cost (~$350/W) inverted metamorphic (IMM) (Microlink Devices Inc., U.S.A.) cell, with a 25-30% PCE at AM0. In both cases, the cells were covered with CORIN XLS Polyimide (NeXolve), an optically clear polyimide (50% transmission UV cutoff of 12µm film at ~377nm) that is stable in radiation exposure and extremely resistant to atomic oxygen erosion.

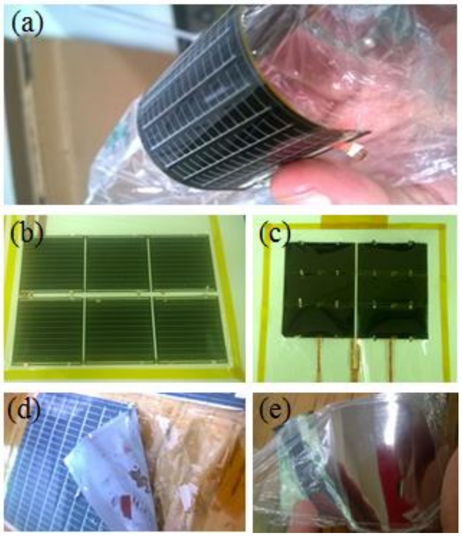

Figure 2: (a) Generation II LISA-T material assembly. (b) CIGS based sub-coupon. (c) IMM based sub-coupon. (d) PV bonded *via* adhesive and (e) PV bonded adhesivelessly.

Development moving forward on generation III assemblies will include the same material set, with further refinements and optimizations. The team is currently working a refined covering and laydown process to combat fabrication induced degradation. In the current process, the best cells finish fabrication with a 0-2% relative enhancement in power generation, while the worst end with a 5-10% degradation. Current refinements are reducing this variation and pushing the average towards the enhancement side of this spectrum. An anti-reflective patterning of the CORIN XLS coating is also in development. This optimization will improve light coupling, especially at an off-normal angle of incidence where Kelly Cosine losses degrade performance. This is particularly important for the non-pointed configuration where the photon incidence angle will vary dramatically as the spacecraft tumbles. Initial results suggest as much as 5% relative improvement in power conversion can be achieved at normal incidence and as high as 10% at deeper angles. Lastly, relevant environment testing of material stackups (substrate + PV + cover) to atomic oxygen exposure, particulate radiation exposure, thermal cycling and the like are currently underway. Updates on these assemblies and relevant testing are expected to be released early in 2017.

GEOMETRY DEVELOPEMNT

Generation I explored both the pointed (planar) and non-pointed (shaped) configurations of LISA-T (Figure 3a,b). The geometry of the pointed panel is straight forward; however, much of the development process has gone into determining the optimal geometry of the non-pointed.

Early generation I prototypes used a parasol-shaped array (Figure 3b). These initial prototypes led to a deeper trade study to find the most advantageous geometry with respect to packaging efficiency, deployment, PV and antenna integration, and ease of fabrication. Aside from the parasol, geometries such a cube, pyramid, cylinder, sphere, torus and facetted versions thereof were considered.

From the results of this trade study and several early generation II prototypes, a four sided pyramid design was adopted (Figure 1c). The early generation II prototypes revealed folding and deployment complexity as the most important aspects in the trade study, with the other criteria only marginally driving the design. In our perspective, the ability to more simplistically stow and deploy an array greatly outweighed aspects such as PV packing density, simplified electrical routing, etc.

As can be seen (Figure 1c), the quad shuttlecock-like architecture is a heavily modified version of the parasol design. Fewer facets (petals) in the pyramid design opened doors for simpler deployment. While separating the facets opened doors for simpler folding/stowage, modular fabrication/re-work and phased deployment. As with the early parasol, a symmetric array design about the spacecraft has been implemented to help minimize net torques induced by the space environment (e.g. gravity gradient, atmospheric drag, solar pressure, etc.). Each side is designed to be modular and self-contained. Though a central design with a shared central deployment structure is slightly more optimized, self-contained pyramids allow the hardware to be stowed into 1U for a 3U satellite or easily separated into 2x 1/2U's for a 6 or 12U spacecraft. Furthermore, a single 'side' could be deployed out the 'top' of a nadir seeking satellite.

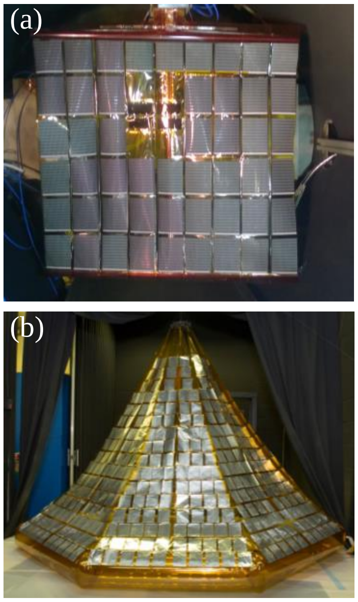

Figure 3: Early generation I LISA-T prototypes. (a) Pointed configuration and (b) parasol omnidirectional.

As opposed to a single cell dimension, the petal fold pattern has been designed around a unit cell size which is approximately the size of a $10cm^2$ 1U face (Figure 4a-c). This allows for different PV and antenna options to be easily incorporated. Though electrical routing on the petal itself will need a unique design for each PV/antenna option, folding (stowage) and deployment – the backbone of the system – is universal. However, some optimization is traded for this flexible configuration. While some thin-film cells can easily (and cheaply) be custom cut to this unit cell size, others cannot and may not completely fill the unit cell size. Nevertheless, this creates a flexible system that can easily be adopted to the next generation of thin-film solar cells.

The generation II pyramid design is also directly convertible from the non-pointed to the pointed array option. A rendering of the pointed configuration is shown in Figure 1d. Only minor changes to the deployed plate are required for this conversion; the basic deployment backbone and the petal structure remain the same.

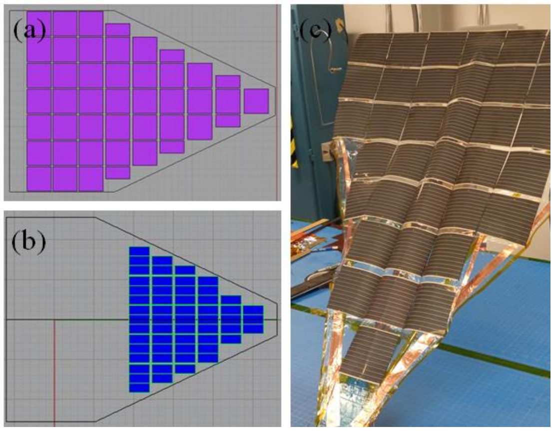

Figure 4: LISA-T petal design. (a) Cell type 1, (b) cell type 2 and (c) cell type prototype supporting its weight in gravity.

The current prototype of the generation II system shows ~50-60W BOL peak power can be generated using the low cost, ~10% cells in the non-pointed configuration. That is, no matter how the spacecraft is pointed or tumbling, the array will generate ~50-60W. Including the deployment overhead, electrical cabling, etc., this array is projected to stow into 1U (~50-60kW/m^3). Using the same cells in the pointed configuration would generate upwards of 275W (275kW/m^3). At the trade of cost, the high performing ~25% cells push these numbers higher: >125W (125kW/m^3) for the non-pointed configuration and >600W (600kW/m^3) in the pointed.

Looking forward, not much is expected to change in the generation III geometry; however, some optimization opportunities do exist. Where the current generation is designed for modularity and flexibility, there is potential for a more targeted design, especially in the high performance case, to further minimize volume and mass while maximizing power generation. A trade study to determine the exact potential is underway.

DEPLOYMENT DEVELOPMENT

Generation I LISA-T used two deployment techniques: (i) a fully inflated article (Figure 3b) and (ii) a hybrid technique combing a foldable kinetic c-boom with an embedded inflation tube (Figure 3a). With the former, concerns of punctures and leaks forced the design to look at carrying make-up gas, curable coatings for the inflatable walls and other alternate solutions. This drove the design described in (ii) and Figure 3a. A passive kinetic boom was first used to partially deploy the array away from the spacecraft. Its energy was not sufficient to completely deploy the array, so active inflation was then used to set the shape. Once the booms locked into place, inflation was no longer needed. This negated the requirement for make-up gas or curing.

The hybrid method was found to be robust and lightweight. The array itself stowed well, however, the inflation method added complexity and was somewhat bulky. Further, there is a negative connotation towards flying pressurized gases, especially as a part of a secondary payload. Sublimation crystals, such as those used for make-up in Project Echo, were an interesting option to alleviate these concerns. However, in generation II, alternate solutions were sought.

To remove the inflation component completely, early generation II prototypes used a fully passive deployment approach, which comprised a nitinol array embedded on the back of the deployable (Figure 5). Nitinol (nickel titanium alloy) is a metal alloy that exhibits shape memory or superelasticity characteristics. After deformation, the shape memory alloy can be brought back to its original set-shape with applied heat. The superelastic alloy requires no heat and deformation recovers much like a spring. Early generation II prototypes explored both types and combinations thereof (e.g. Figure 5b).

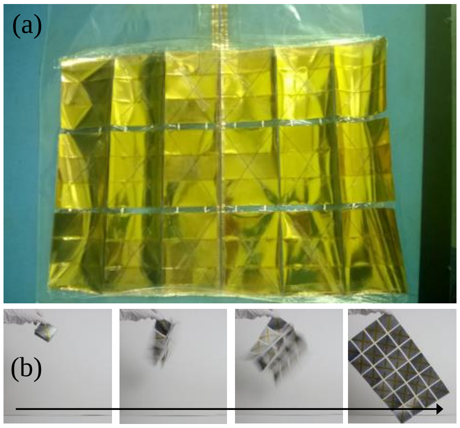

Figure 5: Generation II supereleastic deployment scheme. (a) Back of ~35W pointed supereleastic prototype. (b) Stowed to deployed sequence.

Although thin, lightweight and effective on smaller scale pointed arrays, the nitinol deployment scheme had limited stiffness and lacked scalability. Applicability to the non-pointed configuration was also somewhat limited. As a result, the current generation II deployment design returns to the kinetic c-style booms used in generation I. Bistable, tape springs are currently being used to form the central deployment system described above. The design is a modified version of the Air Force Research Laboratory's self-contained linear meter-class deployable (SIMPLE) boom. The booms are rolled and spring loaded against the deployment plate and petals. Once fully deployed and locked into place, the petals are then unfolded from the central plate *via* foldable, rollable elgiloy c-booms. Compared with the passive nitinol array, some extra stowage overhead is required. However, stiffness and stability has empirically been shown to be quite high (quantitative analysis is ongoing). Scalability between tens of watts and several hundred (perhaps as high as 1kW) is expected.

Generation III deployment will explore including active control to the deployment again. Currently, there is some concern that the kinematics of a passive, spring force deployment may cause the cubesat to tumble uncontrollably. Furthermore, these unchecked deployment forces may cause booms to buckle or petals to oscillate into each other – damaging portions of the array. Initial intuition indicates the former may prove untrue while the latter may drive the need for a somewhat more controlled deployment – that is, a slower release of the stored energy in the booms to protect the deployed hardware. For generation III the team is modeling these kinematics and adding non-inflation based deployment control accordingly.

ELECTRICAL DEVELOPMENT

As mentioned above two main solar cell types are currently being used. In generation I, electrical interconnection between these cells was accomplished with 12µm copper ribbon bonded to the cell pads *via* a space rated conductive epoxy. Power was then routed to the edge of the deployable blanket using bare 25µm copper bus bars, bonded to the Kapton substrate with a pressure sensitive adhesive. A typical wiring harness was then soldered to the copper traces to route power back to the spacecraft.

Generation II has explored an expanded set of electrical interconnects, and is currently using 25µm silver ribbon for CTE matching. Two interconnects per cell connection are used for redundancy and the interconnects are looped. The loops not only allows for thermal movement, but also provides strain relief over fold lines. The conductive epoxy bonding method has been replaced with a micro-welding process, providing a thin, lightweight interconnection that is known to be robust in the space environment.

Integrated copper power busses are still being used in generation II to route power from the PV strings to the edge of the deployable. The buses are now, however, adhesivelessly laminated to the CP1 substrate for thickness and mass savings. The traces are also being covered with an insulating polyimide to protect from shorting and potential arcing events.

Also for mass and stowed volume savings, Generation II has replaced the more traditional wiring harness with a thin-film ribbon cable – again fabricated from copper traces encapsulated by NeXolve's polyimides. This ribbon cable brings power from the deployed petals back to the spacecraft. It can be both folded and/or rolled for stowage (Figure 6), with the latter being preferred to maintain the integrity of the copper lines.

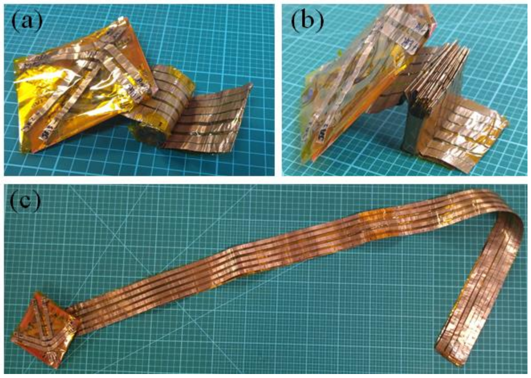

Figure 6: Multi-layered 1 meter ribbon harness prototype. (a) roll stow, (b) fold stow and (c) deployed.

In generation III the electrical team is working to cover/electrically insulate the cell interconnects to protect them from oxidation as well as potential arcing events. The team is also working to incorporate more thin-film PV options, such as a 'middle of the road' option with a cost (~$90-100/W) and performance (~18-20%) between that of the IMM and CIGS cells mentioned above. A thinned version of the current SOA triple junction solar cell as well as a cell that has potential low cost (<$10/W) and moderate performance (~18-20%) are also being evaluated. Initial options to print PV directly to the CP1 substrate are also being evaluated.

ANTENNA DEVELOPMENT

In Generation I, UHF and S-band antennas were incorporated. Custom UHF dipole antennas were created and integrated into the panel. These dipole antennas were created using flexible copper traces. In addition, a commercial UHF monopole antenna was mounted on the chassis for comparison testing. An in-house S-band patch antenna on the chassis very near the panel was also tested. The results of these tests and concurrent simulations demonstrated increased performance of the custom UHF dipole over the commercial off the shelf monopole. It was also observed that the functioning solar cells did not impede performance in either the UHF or S-band. This led to efforts in generation II to reduce the footprint of the antenna structures and further embed/integrate them into the panel.

Therefore, in generation II the use of thermally set super-elastic nitinol was employed. Super-elastic nitinol is flexible for stowage but will spring back to its set shape. This desired shape can be set at high temperatures (~500 C for the currently used nitinol alloy). Therefore, the UHF dipole antennas in generation II are made out of nitinol wire which can serve as both antenna and supporting mechanical structure. As for the generation II S and X band antennas, several designs are still being compared as they are integrated onto the panel. The embedding of typical patch antennas is also possible, however, the thickness and mass of these patches makes them undesirable. Therefore, nitinol wire is again being utilized. In this case, the wire is set into the desired axial helix antenna structure. With both the patch and helical antenna, these structures are embedded onto the panel in the place of a solar cell. However, the helix antenna has lower mass, lower stowed thickness, and higher gain. In each case, multiple antennas are being placed so that spherical coverage can be achieved.

Looking forward, further optimization of the nitinol helix antenna will be conducted with emphases on a minimal thickness ground plane and supporting material to prevent undesired spring-type oscillations. Further evaluations between the patch and helical antenna will also be made.

CONCLUSION

The capability of small satellites is currently limited. Owing to scarce satellite surface area, internal volume and mass allocation, subsystems such as power generation and communications must do more with less. NASA MSFC's Lightweight Integrated Solar Array and Transceiver project seeks to do just that – combining thin-film photovoltaic and antenna elements to create a highly stowable, low mass deployment system. LISA-T is providing more power at a higher stowed density (W/m^3) and higher specific power (W/kg) with a secondary option to leverage low cost solar cells. Further, LISA-T is simultaneously enabling omnidirectional communications and laying the groundwork for high gain design and electronically steered phase arrays. Higher power generation and better communications will enable a new class of high capability small satellites, increasing the value of these lower cost spacecraft.

Acknowledgments

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