Advancements of the Lightweight Integrated Solar Array and Transceiver (LISA-T) Small Spacecraft System

Tiffany Russell Lockett[1], Armando Martinez[1], Darren Boyd[1], Michael SanSoucie[1], Brandon Farmer[2], Todd Schneider[1], Greg Laue[1], Leo Fabisinski[1], Les Johnson[1], and John A. Carr[1]

[1]National Aeronautics and Space Administration (NASA), Marshall Space Flight Center (MSFC), Huntsville, Al, 35812, U.S.A.

[2]ManTech NeXolve Corporation, Huntsville, Al, 35806, U.S.A.

Abstract **— This paper describes recent advancements of the Lightweight Integrated Solar Array and Transceiver (LISA-T) currently being developed at NASA's Marshall Space Flight Center. The LISA-T array comprises a launch stowed, orbit deployed structure on which thin-film photovoltaic (PV) and antenna devices are embedded. The system provides significant electrical power generation at low weights, high stowage efficiency, and without the need for solar tracking. Leveraging high-volume terrestrial-market PVs also gives the potential for lower array costs. LISA-T is addressing the *power starvation epidemic* currently seen by many small-scale satellites while also enabling the application of deployable antenna arrays. Herein, an overview of the system and its applications are presented alongside sub-system development progress and environmental testing plans.**

I. Introduction

The trend of satellite miniaturization continues to enable lower-cost alternatives to the traditional large-scale spacecraft; opening a door to space for many research and commercial payloads. These small-scale satellites, however, are inherently plagued by limited surface area, volume, and mass allocation; limiting solar array real-estate and electrical power generation. Solar array deployment options exist, but are still limited in size and some levy the requirement of solar tracking. Thus, though a lower-cost vehicle to space exists, capabilities remain choked by the small power systems.

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 or more payload allocation. Furthermore, their mechanical flexibility lends itself well to stowage and deployment schemes. Both make thin-film arrays an exciting prospect for small-scale satellites. However, a gap in thin-film array development exists, leaving very few choices for available array structures. [1] The Lightweight Integrated Solar Array and Transceiver (LISA-T) seeks to address this, enabling higher power generation in small-scale satellites at low weights, high stowage efficiency, and without the need for solar tracking.

LISA-T is a tunable, launch stowed, orbit deployed array on which thin-film solar power and communication devices are be embedded (Fig. 1). Initial estimates indicate upwards of 200W of power generation can be packaged into and deployed from 1U and nearly 500W from 2U. Furthermore, the system can also leverage high-volume terrestrial market photovoltaics (PVs), lowering module costs ($/W). The integration of thin-film antennas allows communication arrays to be simultaneously deployed. An option for '3-dimensional deployment' eliminates the need for solar tracking and allows for stronger omnidirectional communications.

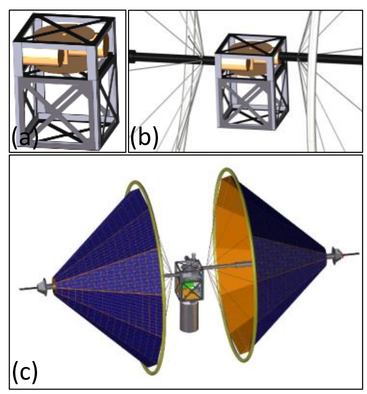

Fig. 1. Conceptual rendering of LISA-T. (a) Stowed, (b) and (c) deployed.

LISA-T builds upon previously published concepts, such as the PowerSphere [2], Inflatable Torus Solar Array Technology (ITSAT) [3,4], and others [5,6,7,8,9] utilizing new engineering concepts and the latest advancements in thin-film materials, devices, and deployment options. The project leverages several existing and on-going efforts at Marshall Space Flight Center (MSFC) for design, development, fabrication, and test. Most notably is extensive solar sail work which is rapidly maturing lightweight, large area deployment technologies [10,11]. The most current LISA-T activity will advance the system technology readiness level (TRL) from 4 through 6+.

TABLE I

SUMMARY OF GEOMETRY SIZING TRADE: TOTAL DEPLOYED ARRAY TO GENERATE 200W POWER FROM 25% PV.

Shape	Packing density (%)	Area (m^2)	Configuration Factor	Total Area Required (m^2)
Cube	90	0.65	5.00	3.25
Pyramid	80	0.79	3.00	2.36
Cylinder*	80	0.92	3.14	3.61
Sphere	80	0.92	4.00	3.66
¾ Torus	80	0.92	2.00	1.83

*DOES NOT INCLUDE CIRCULAR TOP

The project is supported through a NASA space technology development activity called the Early Career Initiative (ECI) sponsored by the Space Technology Mission Directorate (STMD) at NASA Headquarters. The project is being completed in partnership with ManTech\NeXolve (Huntsville, Al, U.S.A.) and is being managed under the Small Spacecraft Technology (SST) program. Herein, the most recent concept(s) and design progress of the LISA-T platform will be discussed.

II. GEOMETRY AND DEPLOYMENT

A step being taken in the development of LISA-T is an option to maintain a constant power generation independent of the incident angle – a '3-dimensional' deployment to simplify Guidance, Navigation, and Control by eliminating the need for array or spacecraft solar pointing. A trade study has commenced to investigate various deployment geometries, which include a cube, cylinder, sphere, triangular pyramid, and torus. Each shape is effected differently by potential packing densities, the configuration knockdown factor (related to projected area and number of deployed sides), as well as the Kelly Cosine Law (Table I). For example, a square side of a cube resembles a more traditional solar panel and cells can be packed to cover more of the surface area (90%+). With an average power generation from a 25% efficient cell of ~307 W/m^2 at the module level, ~0.65m^2 must be illuminated at any given time to produce 200W of continuous power. To configure this into a cube 5 or 6 sides must be deployed simultaneously to eliminate the need for pointing and, hence, at least 3.25m^2 of array must be stowed/deployed. Worst case Kelly Cosine *losses* are when illumination is normal to one side, as angled incidence will illuminate multiple sides generating more power.

To further down select the geometry, antenna and PV integration, along with the ease of fabrication, stowage, deployment will be considered.

Various types of deployment methods will also be reviewed. Mechanical 'boom-type', inflatable, and hybrid options are currently being explored. Some key factors for selection are stiffness, mass, TRL, reliability, stowed volume and scalability. Some of the booms that have been researched are the Carbon Fibre Reinforced Polymer (CFRP), Collapsible Rollable Tube (CRT), Nano stem, and telescoping tube mast. Currently, the top contender for the deployment mechanism is the tape boom known as the Triangular Rollable and Collapsible (TRAC) Mast manufactured by ManTech/NeXolve under license to AFRL [12]. The reliability, high TRL level, and ability to self-deploy utilizing strain energy were key characteristics. NeXolve with support from AFRL successfully manufactured and integrated metallic TRAC booms into the deployer design utilized for NASA's Nanosail-D deorbit demonstration providing a high TRL baseline to support the LISA-T design trades. Alternative to deployable TRAC booms or masts fell outside the needed envelope or were not scalable to our required needs.

Challenges that face the deployment mechanism are the limited volume available for the mechanical deployment system, keeping the structure rigid once deployed, and how the device would deploy, whether via inflation, strain energy, or with a mechanism. The team is currently developing design concepts for the triangular pyramid, cube, and cylinder. The current LISA-T development effort will produce a geometric and mechanical design by the date of the conference. The intention will be to share the trade study results and design implications.

III. PHOTOVOLTAIC AND MATERIALS

In parallel to the geometry and deployment development, much of the current effort is focused on the PV assembly – that is, substrate material + PV cell and interconnections + cover material. A lightweight, highly stowable assembly that is robust to deployment forces and short term (<6 months) exposure to the space environment is initially sought.

The field of thin-film photovoltaics is somewhat broad and encompasses technologies from the more traditional, such as amorphous silicon (a:Si) or copper indium gallium (di)selenide (CIGS), to the emerging, such as organic and perovskite based cells. Several technologies are being utilized and traded by the LISA-T team – each with their own distinct advantages. A metric based matrix is being built to offer options for different types of missions. For example, a high performance, high reliability mission (superior W/m^2, W/m^3, W/kg, and lifetime) with a higher budget ($/W allocation) can be envisioned. Space-qualified, 30%+ inverted metamorphic (IMMs) are best suited for such an application. In contrast, a lower budget mission with less emphasis on performance metrics and more emphasis on cost might also be envisioned. Adapted terrestrial market, low cost (<$20/W) CIGS may be best suited. Both technologies as well as two silicon based cells are being carried through the current development of LISA-T. Of course, each option will still enable higher total power generation than current state-of-the-art options.

A similar matrix of options is also being compiled for the supporting and cover materials. For example, a Low Earth Obit (LEO) mission with exposure to atomic oxygen is easily envisioned. Colorless Organic Inorganic Nanocomposite (CORIN) (ManTech\NeXolve, Huntsville, AL U.S.A.), a fluorinated polyimide which NASA has demonstrated to have the highest atomic oxygen resistance of the all polymers flown on Materials on the International Space Station Experiment 7 (MISSE 7) [13], is a well suited substrate for such a case. For higher altitude or deep space missions, Colorless Polyimide 1 (CP1), a fluorinated, durable polyimide with years of space heritage dating back to MISSE 1 [14], is being considered. Each polyimide can be formulated or coated with vapor deposited materials to exhibit a specific emissivity and alpha, enabling a degree of tunability into the thermal design.

Cover materials are also included in this matrix. Current trades indicate the short missions LISA-T is initially being designed for may tolerate flying bare cells. However, it remains clear that longer term missions would benefit from a protective cover. The most promising material is a new polymer system being developed by ManTech\NeXolve – Optinox SR. The material is thin, lightweight and easily incorporated into the LISA-T system. Optinox has a low Ultra Violet cutoff at <300nm for a 25µm film and can potentially be doped to improve its radiation-resistance; making it a top candidate as a protective, flexible encapsulant for the PV.

Integrating these assembly materials and electrically interconnecting the PV cells is the focus of current efforts. Initial pathfinder samples are being produced on 25 µm Kapton HN (DuPont, U.S.A.) via a low outgassing pressure sensitive adhesive bonding method (Fig. 2). Electrical interconnection is currently being done with 12µm copper ribbon bonded via a space rated conductive epoxy. Initial results are promising with less than 2% (relative) PV degradation through the entire integration process and 0% loss after repetitive (up to 10x) fold/unfold cycles. The 2% fabrication loss was exhibited in current only and has been tracked to a light film left atop the cells after the bonding process.

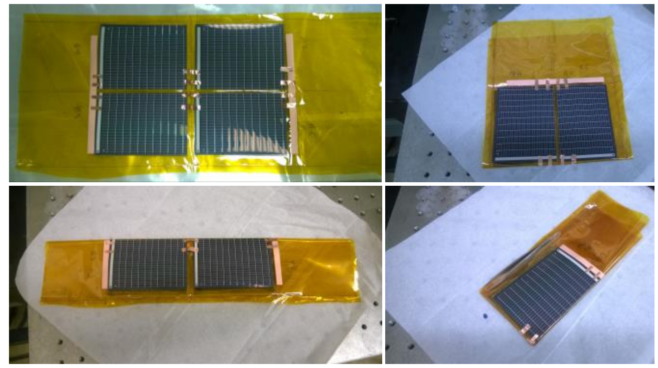

Fig. 2: Pathfinder PV assembly. Thin-film PV bonded to 25µm Kapton with 12µm copper ribbon interconnects.

Second generation assemblies are currently in production. To facilitate lighter weights and higher packing densities, these assemblies are being produced on a 2-5µm CP1 substrate via an adhesive-less bonding method. NeXolve's clear polyimides are unique in that they are not thermoset. This gives the ability for the polymers to be re-dissolved or undergo low temperature cures, enabling the material to be bonded to itself without the need for an adhesive. Thus, NeXolve's polyimide resins can be applied directly to the flexible PV back plane which can, in turn, be solvent or heat welded directly onto the polyimide back sheet; saving the thickness and weight of adhesive. This assembly will soon undergo thermal cycling through a simulated LEO orbit to determine its thermal durability.

In addition to adhesive-less and polyimide materials more traditional bonding adhesives will be explored such as the silicon adhesive systems currently utilized by NeXolve in the construction of the James Webb Space Telescope sunshade currently being manufactured by ManTech/NeXolve. The team has a significant heritage in space qualifying materials having successfully Flight qualified all JWST Sunshield constructions which include adhesive–less seams and bonded assemblies. This experience base will be leveraged in key material manufacturing trades as the design matures.

These assemblies are also exploring an expanded set of electrical interconnection materials and connection methods. The material set now also includes <25um thick silver clad Kovar, aluminum, and silver ribbon to trade conductivity, weight, and coefficient of thermal expansion matching to both the PV contact as well as the potential cover materials. Interconnection methods now also include low temperature reflow soldering and micro-resistance welding to trade weight, manufacturing ease, and resistance to environmental effects. Long term goals are heavily focused on a welding process for its proven longevity in the space environment and lighter weight, however, both epoxy and reflow soldering lend themselves well to roll production of LISA-T articles.

Integrated power buses and thin-film wire harnesses are also being developed as a part of the LISA-T PV assembly. NeXolve's polyimide resins can be applied directly to metallic foils, which can then be patterned and etched to essentially form a multi-layer printed circuit board on the assembly substrate; a potential method for interconnecting cells and strings to a power bus. A similar concept is also being used to create encapsulated traces on or near the deployment booms – essentially, a thin-film wire harnesses to carry the generated power into the satellite. This significantly reduces weight and enables higher packing efficiency.

IV. Integrated Array Regulation and power management

In order to produce continuous power without pointing, the LISA-T array carries cells mounted over most of its exposed surfaces. Only about 1/4 of the array's cells are illuminated at any given time, and the degree of illumination varies considerably between cells on different parts of the array's surface. This means that at any given time, each string of the array can produce a different voltage and current, and that the voltage and current for a particular string can change quickly over time as the spacecraft rotates and moves in its orbit. Unfortunately, the spacecraft and payload electrical components generally require a constant, regulated voltage. This problem is compounded in small, inexpensive satellites by the availability of space-qualified components requiring several different voltages (12V, 28V, 50V, etc) and the need to manage the charge for secondary batteries for use when the craft is in eclipse.

To solve these problems, LISA-T carries a power management subsystem that integrates the following functions into a single package with the array:

1) Array Shunt Regulation
2) Real-Time programmable voltage conversion and regulation for 2 different power busses. Voltage of each bus may be set remotely at any time.
3) Battery charge control. This too may be controlled remotely and modified for specific flight operations.

In the LISA-T architecture, the cells are grouped into strings of only a few cells. The strings are not connected together as they are in other architectures. Instead, each is terminated with a capacitor for temporary energy storage. The power management subsystem samples each string in turn to see if it has produced any energy. If it has, it converts the energy to the voltage required by each output bus and sends it to the output regulator. If the energy is not needed by the spacecraft or its payload, the energy is dumped to a resistive shunt and radiated away as heat. Each string is sampled every millisecond in this fashion.

There are additional advantages in this architecture. By integrating all of the power regulation, conditioning and storage functions with the array, the spacecraft doesn't have to provide these. This saves money and valuable space in a space-limited bus architecture such as CubeSat. Integrating these also allows the operator full control over the power subsystem during flight. The operator can change the bus voltage to accommodate different instruments and manage the battery charge profile for different situations. Since individual cells are not in use during the entire mission, they degrade more slowly and produce more power at end of life.

V. Transceiver

Solar cells and antenna structures often compete for valuable surface area, volume and mass allocation – especially in small-scale space systems [15]. The objective of the LISA-T transceiver subsystem is to integrate solar cell arrays and antenna elements onto one three dimensional structure. This will save resources by sharing deployment hardware, eliminate mechanical pointing, and create more antenna real-estate. Incorporating antenna elements into multiple positions on a three dimensional deployable structure will allow for both omnidirectional communication and possible phase array steering.

Spacecraft systems vary across a wide range of frequencies and bands. Various antenna types and radio frequency (RF) bands are being investigated and evaluated for optimal efficiency in both communication and integration. These bands include but are not limited to UHF/VHF, S-band, and X-band. Pole, patch, and slot antennas are being evaluated. Stand alone and phase array implementations are also being explored. The antenna structures may be integrated into the deployment support structures or interspersed among the solar cells. Preliminary trade studies were conducted considering these options.

From those trade studies, initial testing is being performed using custom in-house constructed lightweight deployable UHF band dipoles, commercial UHF band monopoles, in-house constructed S-band patches, and in-house constructed X-band patches. The UHF band dipoles were created using flexible copper traces on 1 mil Kapton (Fig. 3). Preliminary bench-top testing was conducted with each antenna to ensure a reflected power loss measurement (S11) of 20 – 45 dB at the desired center frequency. FM (Frequency Modulation) communications between antennas was achieved and is being employed for initial testing. Lab experimentation and/or Ansoft HFSS simulations were used to conduct experiments varying the following antenna design parameters: dipole trace width, dipole/monopole trace length, dipole trace spacing, dipole unbalanced feed line design, monopole ground plane size, S-band patch size, S-band patch substrate, location on the space craft, effects of surrounding solar cell wiring, and effect of surrounding craft structures. These experiments are being used to guide future development and aid in current environmental testing.

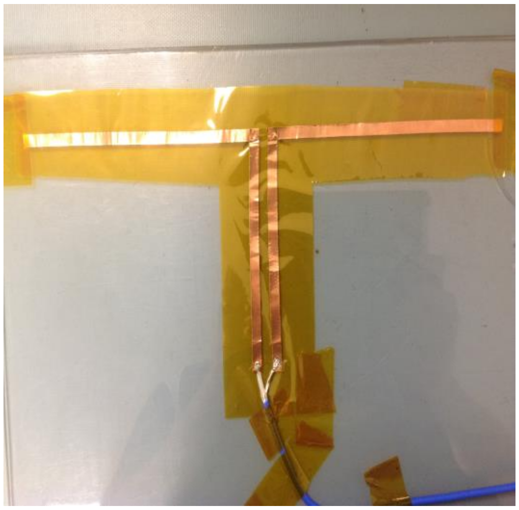

Figure 3: UHF band dipoles made of flexible copper traces on 1mil Kapton.

In order to test the environmental effects on the antennas and the electromagnetic interference of the proposed spacecraft including the solar cell system, the antennas were integrated into a preliminary test article and are being tested in a High Intensity Solar Environment vacuum chamber. The commercial monopole and S-band patch antenna were mounted on the cubesat frame. The custom flexible dipole antenna was integrated onto the deployable solar array substrate. Duplicate antennas are installed on the opposite side of the chamber for communications tests. All UHF antennas in the chamber are being tuned to match the embedded antenna integrated onto the solar cell substrate with the spacecraft model. Bit error rates, communication speeds, antenna center frequency, antenna bandwidth, and signal to noise measurements will be taken with and without solar cell illumination. This will provide comparative measurements of the interference effects.

VI. TESTING

The LISA-T project will involve a significant amount of testing. A life-cycle test bed is being built and a considerable amount of space environmental effects testing will be performed at MSFC. The life-cycle test bed will support the testing of custom, small-satellite power systems. It allows integrated power systems to be tested as per expected orbit, in a space environment with real-time simulated zero atmosphere (AM0) solar illumination, power load profiles, and electrical characterization. The system can be seen in Figure 4 and 5.Using liquid nitrogen cooled cold plates, thermal cycling will also be possible. All of this makes the test bed valuable for development and testing of advanced power system research.

Figure 4: Top portion of the life-cycle test bed. Removed for modifications.

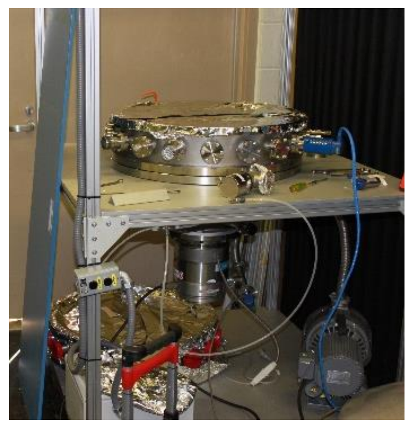

Figure 5: Bottom portion of the life-cycle test bed.

A test plan for environmental effects testing is also being developed. Testing such as particulate radiation, UV radiation, angle of incidence, solar environment, and atomic oxygen is being developed by tailoring portions current solar cell and panel standards.

The test bed uses a Spectrolabs X-25 solar simulator to provide the solar illumination. The sample will be placed on top of a liquid nitrogen (LN2) cold plate that also has strip heaters on the bottom. This will allow testing at cryogenic as well as hot (the target is up to 150°C) temperatures, and thermal cycling should also be possible.

For LISA-T, a sample will be thermally cycled to simulate a Low Earth Orbit (LEO) environment. This will involve cycling between -95oC and 110oC. A further goal of -150oC to 150oC will be attempted, with an ultimate goal of achieving -175ºC, which would correspond to the cold temperature while in geosynchronous equatorial orbit (GEO). Thermal cycling will be done while under high vacuum (~10^-6 torr) and with AM0 solar illumination.

Charged particle radiation consists of protons and electrons with a wide range of energies. The Combined Environmental Effects Test Cell uses two Pelletron accelerators, an electron accelerator of 200 keV to 2.5 MeV energy, and a proton accelerator of 40 to 800 keV energy. An electron flood gun provides 1 to 50 keV electrons. The fluxes for the electron and proton accelerators are $2x10^8$ to $3x10^{14}$ e^- (or p^+) / (cm^2 s). The setup also has a mercury-xenon lamp for near-ultraviolet (NUV) radiation. The NUV source produces photons over the range of 200 to 2,400 nm [16,17].

The testing of LISA-T will also utilize the High Intensity Solar Environment Test (HISET) system, which combines the elements of the solar wind environment with a high intensity, high power solar radiation source [4]. The simulated solar wind includes low energy electrons (1-100 keV), protons (1-30keV), NUV radiation, and vacuum ultraviolet (VUV) radiation. The HISET system can also be used for evaluating materials at temperatures exceeding 1000oC.

VII. Conclusion

The LISA-T project is an innovative approach to integrating a small satellite's solar array and transceiver elements. The design will be scalable and adaptable to mission requirements. The technology will enable small satellites to perform more in-depth science with the availability of greater electrical power and communication arrays. Extensive work is currently underway designing the geometric shape, the deployment mechanisms, stowage, testing the state of the art thin film PVs and transceiver elements, and substrate development. The LISA-T will receive a battery of space environments tests on the component level as well as at the integrated system level. At the end of the current two year effort a fully tested, TRL 6 qualified engineering unit will be developed. Advancements, design configurations, and initial test data of this effort will be presented.

References

[1] S. Bailey *et al*, "The Future of Space Photovoltaics," in *Photovoltaic Specialists Conference (PVSC),* 2009, p. 1909.

[2] E. Simburger *et al*, "Thin Film Technology Development for the PowerSphere," *Materials Science and Engineering: B*, 2005, Vol. 116, Iss. 3, p. 265-272.

[3] P. Malone and G. Williams, "Lightweight Inflatable Solar Array," in *Journal of Propulsion and Power*, 1996, Vol. 12, No. 5, pp. 866-872.

[4] P. Malone, *et al*, "Developing A Solar Array," in *Small Satellite Conference Technical Session VIII: Subsystems II*, 1993.

[5] M. Breen, A. Streett, D. Cokin, R. Stribling, A. Mason, and S. Sutton, "IBIS (Integrated Blanket/Interconnect System), Boeing's Solution for Implementing IMM (Inverted Metamorphic) Solar Cells on a Light-Weight Flexible Solar Panel," in *Photovoltaic Specialists Conference (PVSC), 2010 35th IEEE*, 2010, pp. 723-724.

[6] J.W. Zuckermandel, *et al*, "Design, Build, and Testing of TacSat Thin Film Solar Arrays," in *Proc. Of the 4th Int Energy Conversion Engineering Conference and Exhibit*, 2006, p. 26-29.

[7] M.S. Grahne and D.P. Cadogan, "Inflatable Solar Arrays: Revolutionary Technology?," in *SAE Technical Paper 1999-01-2551*, 1999.

[8] R. Stribling, "Boeing High Power Thin Film Solar Array," in *4th International Energy Conversion Engineering Conference and Exhibit (IECEC)*, 2006, p. 26-29.

[9] A.L. Adler, *et al*, "AFRL PowerSail Structure for Large Solar Arrays," in *Space 2003*, 2003, AIAA 2003-6356.

[10] D.Alhorn, *et al*, "Nano-Sail D: The Small Satellite That Could!," in *25th Annual AIAA/USU Conference on Small Satellites, Technical Session VI*, 2011.

[11] L. Johnson, R. Young, E. Montgomery, and D. Alhorn, "Status of solar sail technology within NASA," *Advances in Space Research*, vol. 48, pp. 1687-1694, 2011.

[12] Murphy. T. W., Banik, J.A., "Performance Validation of the Triangular Rollable and Collapsible Mast," in *24th Annual AIAA/USU Conference on Small Satellites*, 2010, SSC10-II-1.

[13] G.T. Yi, *et al*, "Overview of the MISSE 7 Polymers and Zenith Polymers Experiments After 1.5 Years of Space Exposure," in *NASA/TM 2013-217848*, 2013.

[14] K. K. deGroh, J. A. Dever, D. A. Jaworske, S. K. Miller, E. A. Sechkar, and S. R. Panko, "NASA Glenn Research Center's Materials International Space Station Experiments (MISSE 1-7)," 2008. [15] Budianu, A.; Meijerink, A.; Bentum, M.J.; Klein, J.M.; Engelen, S., "Integrated Downlink Antennas in the Deployable Solar Panels of a Cubesat," *Aerospace Conference, 2014 IEEE*, vol., no., pp.1,11, 1-8 March 2014.

[16] Miria M. Finckenor, et. al. Test and Analysis Capabilities of the Space Environmental Effects Team at Marshall Space Flight Center. NASA TP-2002-212076

[17] Miria M. Finckenor, et. al. Space Environmental Effects Testing in Support of the International Space Station. 38th Aerospace Sciences Meeting & Exhibit, January 10-13, 2000, Reno, NV. AIAA-2000-0242.