Deployable Propulsion, Power and Communication Systems for Solar System Exploration

Les Johnson
NASA George C. Marshall Space
Flight Center
Huntsville, AL 35812
256-544-7824
Les.Johnson@nasa.gov

John A. Carr
NASA George C. Marshall Space
Flight Center
Huntsville, AL 35812
256.544.7114
John.A.Carr@nasa.gov

Darren Boyd
NASA George C. Marshall Space Flight Center
Huntsville, AL 35812
256.544.6466
Darren.R.Boyd@nasa.gov

Abstract— NASA is developing thin-film based, deployable propulsion, power, and communication systems for small spacecraft that could provide a revolutionary new capability allowing small spacecraft exploration of the solar system. By leveraging recent advancements in thin films, photovoltaics, and miniaturized electronics, new mission-level capabilities will be enabled aboard lower-cost small spacecraft instead of their more expensive, traditional counterparts, enabling a new generation of frequent, inexpensive deep space missions. Specifically, thin-film technologies are allowing the development and use of solar sails for propulsion, small, lightweight photovoltaics for power, and omnidirectional antennas for communication.

Like their name implies, solar sails 'sail' by reflecting sunlight from a large, lightweight reflective material that resembles the sails of 17th and 18th century ships and modern sloops. Instead of wind, the sail and the ship derive their thrust by reflecting solar photons. Solar sail technology has been discussed in the literature for quite some time, but it is only since 2010 that sails have been proven to work in space. Thin-film photovoltaics are revolutionizing the terrestrial power generation market and have been found to be suitable for medium-term use in the space environment. When mounted on the thin-film substrate, these photovoltaics can be packaged into very small volumes and used to generate significant power for small spacecraft. Finally, embedded antennas are being developed that can be adhered to thin-film substrates to provide lightweight, omnidirectional UHF and X-band coverage, increasing bandwidth or effective communication ranges for small spacecraft. Taken together, they may enable a host of new deep space destinations to be reached by a generation of spacecraft smaller and more capable than ever before.

TABLE OF CONTENTS

1. INTRODUCTION

The Near Earth Asteroid (NEA) Scout reconnaissance mission will demonstrate solar sail propulsion on a 6U CubeSat interplanetary spacecraft and lay the groundwork for their future use in deep space science and exploration missions. Solar sails use sunlight to propel vehicles through space by reflecting solar photons from a large, mirror-like sail made of a lightweight, highly reflective material. This continuous photon pressure provides propellantless thrust, allowing for very high ΔV maneuvers on long-duration, deep space exploration. Since reflected light produces thrust, solar sails require no onboard propellant.

The Lightweight Integrated Solar Array and anTenna (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, which drives 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 by deploying large-area arrays from a reduced volume and mass envelope – greatly enhancing power generation and communications capabilities of small spacecraft.

The NEA Scout mission, funded by NASA's Advanced Exploration Systems Program and managed by NASA Marshall Space Flight Center (MSFC), will use the solar sail as its primary propulsion system, allowing it to survey and image one or more NEA's of interest for possible future human exploration. NEA Scout uses a 6U cubesat (to be provided by NASA's Jet Propulsion Laboratory), an 86 m^2 solar sail, and will weigh less than 12 kilograms. NEA Scout

will be launched on the first flight of the Space Launch System in 2018.

Similar in concept to the NEA Scout solar sail, the LISA-T array is designed to fit into a very small volume and provide abundant power and omnidirectional communications in just about any deployment configuration. The technology is being proposed for flight validation as early as 2019 in a low earth orbit (LEO) demonstration using a 3U cubesat, of which less than 1U will be devoted to the LISA-T power and propulsion system.

It is possible that all three technologies can be simultaneously used on future small spacecraft missions, increasing their range (via the solar sail), their science return (via the increased power generation), and their data volume (via the deployable antenna).

2. SOLAR SAIL PROPULSION

Solar sails use sunlight to propel vehicles through space by reflecting solar photons from a large, mirror-like sail. This continuous photon pressure provides propellantless thrust, allowing for very high ΔV maneuvers on long-duration, deep-space exploration.

The sail material is an aluminized polyimide approximately 3 microns thick. The extremely large, lightweight reflective materials take advantage of the continuous presence of sunlight to derive propulsion, making them capable of performing a wide range of advanced maneuvers – navigating from location to location in near-Sun space, hovering, or conducting heliocentric orbital plane changes more efficiently than conventional chemical propulsion. Eventually, a solar sail propulsion system could propel a space vehicle to tremendous speeds, theoretically much faster than any present-day propulsion system. Since the Sun supplies the necessary propulsive energy, solar sails require no onboard propellant, thereby potentially increasing useful payload mass.

The concept of solar sailing has existed for approximately 100 years, beginning with Tsiolkovsky and Tsander in the 1920s. In the late 1970s, a team at JPL studied the use of a solar sail for a rendezvous with Halley's Comet. [1] In the early-to-mid 2000's, NASA's In-Space Propulsion Technology Project developed two different 20 m solar sail systems and tested them in the Glenn Research Center's Space Power Facility at Plum Brook Station, Ohio. [2] Solar sail propulsion was then selected as a candidate for flight validation by NASA's New Millennium Program on their proposed Space Technology 9 (ST-9) flight. Unfortunately, funding for both the In-Space Propulsion Technology Project

and the New Millennium Program were terminated shortly thereafter due to NASA's changing priorities.

Solar sailing has been tested in space. The Japanese Aerospace Exploration Agency, JAXA, launched in 2010 a solar sail spacecraft named Interplanetary Kite-craft Accelerated by Radiation of the Sun (IKAROS), becoming the first in-flight demonstration of solar sailing. [3]

Using the hardware left over from the two sails developed by the In-Space Propulsion Program, NASA MSFC also flew a solar sail in 2010 called *NanoSail-D*. NanoSail-D deployed a 10 m^2 sail in LEO, demonstrating autonomous deployment of a sail but not active solar sailing. [4] The Planetary Society's privately-funded 32 m^2 LightSail-A flew in 2015 aboard a 3U CubeSat and performed a similar deployment demonstration. Funded by NASA's Small Business Innovative Research, CU Aerospace and The University of Illinois are developing the CubeSail which consists of two nearly-identical CubeSat satellites to deploy a 250-m long, 20 m^2 sail. [5] The design can be scaled to build a heliogyro solar sail that can potentially achieve square kilometer sail areas. The CubeSail is not yet scheduled for flight.

3. DEPLOYABLE POWER SYSTEMS

The use of thin-film based solar arrays for spacecraft applications has long been recognized as an advantageous power generation option.[6] 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.

This allows an improvement to both specific power (W/kg) as well as stowed power density (W/m^3), enabling higher power generation for small spacecraft. Though several larger scale thin-film or partial thin-film arrays are in development, [7-9] sub-kilowatt thin-film arrays remain scarce. The Marshall Space Flight Center (MSFC) Lightweight Integrated Solar Array and anTenna (LISA-T) seeks to fill this void, both increasing as well as simplifying small spacecraft power generation.

LISA-T marries the most recent advances in the solar sail and photovoltaics community to create a fully thin-film array. The technology is building upon previously published concepts, such as the PowerSphere, [10] Inflatable Torus Solar Array Technology (ITSAT), [11] and others[12, 13]. Figure 1 shows a conceptual rendering of the array.
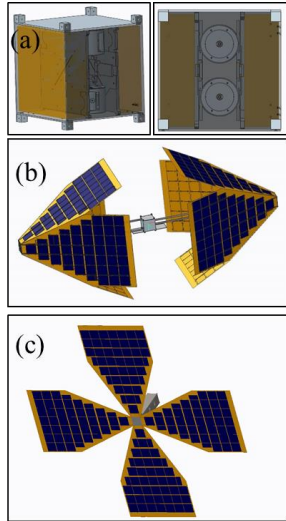
Figure 1: Conceptual rendering of LISA-T array (a) deployed, (b) omnidirectional deployed, and (c) planar deployed.

Two configurations are currently under development: (i) the omnidirectional (non-pointed) and (ii) the planar (pointed). The former stows into a single CubeSat U, while the latter into 1/2U. The omnidirectional array is based on a three-dimensional shape such that no matter how the craft is orientated, power will be generated. This relaxes the need for pointing and greatly simplifies power generation.

Power levels up to 125W peak beginning of life are currently achievable in this configuration. The planar array is based on a traditional flat configuration. Though it requires solar pointing, it maximizes solar cell use and the array parametrics. Power levels up to 300W are currently achievable in this configuration. Options for leveraging both a *high performance* (~28% efficient @ ~$250/W) triple junction thin-film solar cell as well as a *low cost* (~10% efficient @ ~$15/W) single junction are being developed for both configurations. Stowage efficiencies approaching 400kW/m^3 with specific powers approaching 250W/kg are currently achievable

Work to date has brought both configurations to Technology Readiness Level (TRL) 5. Current testing will push the arrays to TRL6 by the end of calendar year 2016. Figure 2 shows the TRL5 omnidirectional prototype: a 60W array based on the low cost cell option. Further details on the array architecture are published elsewhere. [14]
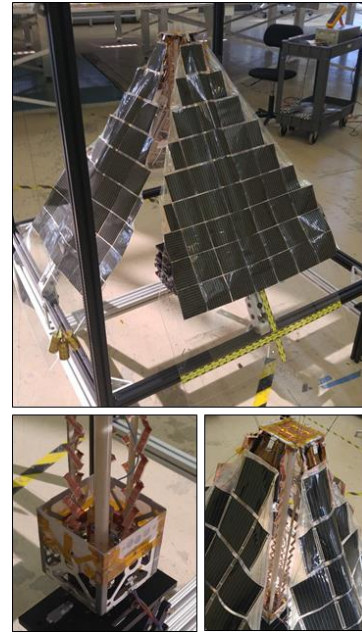

Figure 2: Deployed TRL5 LISA-T omnidirectional configuration prototype.

Array development is being supplemented by pathfinder environmental testing to project in-space lifetimes. A matrix of polyimide material options for both solar cell protection as well as base substrates is being tested. Thermal modeling, deployed stiffness modeling, reentry/trajectory analysis, and dynamics estimations are also being completed. Lifetimes in LEO are currently expected in range of months – limited by orbital drag induced reentry and atomic oxygen erosion. Lifetimes in higher altitude Earth orbits and on interplanetary trajectories are currently expected in the range of several years – limited by particulate and ultra violet radiation exposure. Both the material set and solar cell type can be adjusted to tailor mission lifetime needs.

4. DEPLOYABLE ANTENNAS

Non-pointed missions benefit from antenna system designs with customizable radiation patterns. Antenna arrays provide opportunities for custom radiation patterns, overall gain increases, diversity reception, directional interference cancelling or steering, and incoming signal direction determination. The created surface area of these deployable propulsion and power systems creates new opportunities for the inclusion and positioning of multiple lightweight deployable antennas.

LISA-T integrates lightweight axial mode helical antennas into the deployable power system. These lightweight antennas are flexible for stowage and can be positioned on

either the center point of a panel package (blue lines) or on the panels themselves (red lines) as shown in Figure 3. Antennas on the panels can be placed on either side of the panel as desired.
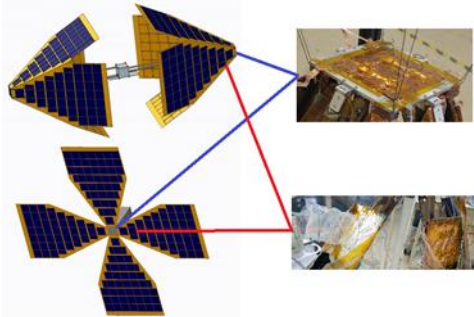

Figure 3: Sample locations of helical antenna placement on LISA-T omnidirectional and planar configurations.

Custom lightweight helical antennas have been created for S band and X band communications. Simulations show both S band and X band helical antennas to have a main beam gain greater than 10db. By placing multiple antennas in various positions on the structure, desired coverage patterns or phased array implementations can be achieved.

In addition to S and X bands, integrated UHF dipole antennas with a simulated gain of 1.6db have also been developed. These dipole antennas can be integrated into the panel between or beside solar cell elements. Further details on the antenna development are published elsewhere. [14]

5. Flight Demonstrations

NASA is considering sending humans to a Near Earth Asteroid (NEA) as part of a long-range plan that will culminate in humans visiting Mars and its Moons in the 2030's. Before committing a crew to visit a NEA or Mars moon, carrying out precursor robotic missions is important to assess candidate objects adequately enough that crew systems appropriate for target environments can be developed. The NEA Scout will use its solar sail propulsion system to send the spacecraft to flyby an asteroid and image it. The mission is planned for launch in 2018 (Figure 4).
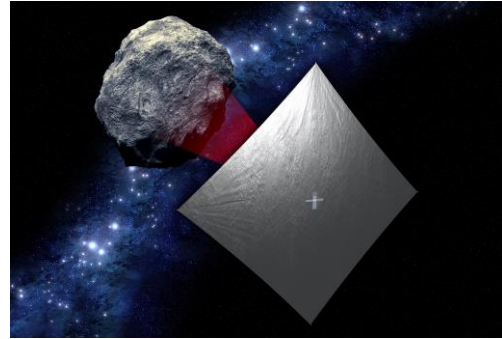

Figure 4. Artist concept drawing of the NASA Near Earth Asteroid Scout mission.

NEA Scout will fly on the first flight of NASA's Space Launch System (SLS) in 2018 and deploy from it after once it has escaped Earth orbit. After NEA Scout's first encounter with the moon, the 86 m^2 solar sail will deploy. Figure 5 shows a fully deployed NEA Scout solar sail at NASA MSFC during testing in the summer of 2016.

Figure 5. The 86 m^2 NEA Scout solar sail during testing at NASA MSFC.

Once the system is checked out, the spacecraft will perform a series of lunar flybys until it achieves optimum departure trajectory to the target asteroid. The spacecraft will then begin its two year-long cruise. NEA's Scout's solar sail will provide continuous low thrust to enable a relatively slow flyby (10-20 m/s) of the target asteroid.

The Planetary Society plans to fly their second 3U cubesat sailcraft, LightSail-2, in 2017. LightSail-2 will again be an Earth orbital deployed sail, but this time they plan to perform some active propulsive maneuvers. The University of Surrey has also developed a 3U cubesat sail, called InflateSail, which is schedule to fly in early 2017.

NASA is studying a potential Earth-orbital flight demonstration of the LISA-T in 2018 or 2019. The demo would consist of a CubeSat Class 1U power and antenna module attached to a 2U spacecraft bus. The current plan would have the 60W module shown in Figure 2 packed in the

4

1U power module and deployed once the CubeSat is in low Earth orbit.

6. CONCLUSIONS

Deployable structures for spacecraft is not a new idea. The technology to finally enable manufacturing, packaging and deploying them from very small spacecraft, including CubeSats, is finally mature. Innovative, multi-functional deployables may provide propulsion, power and communication, greatly increasing the capability of CubeSats for science and exploration and potentially enabling an entirely new class of deep space exploration and science missions.

ACKNOWLEDGEMENTS

REFERENCES

[1] L. Friedman *et al.,* "Solar Sailing-The Concept Made Realistic," AIAA-78-82, 16th AIAA Aerospace Sciences Meeting, Huntsville, AL, January 1978.

[2] L. Johnson, M. Young, and E. Montgomery, "Recent Advances in Solar Sail Propulsion Systems at NASA," *Acta Astronautica*, Vol. 61, 2007, pp. 376-382.

[3] Y. Tsuda *et al.,* "Achievement of Ikaros – Japanese Deep Space Solar Sail Demonstration Mission," 7th IAA Symposium on Realistic Near-Term Advanced Scientific Space Missions, Aosta, Italy, 2011.

[4] D. Alhorn *et al.,* "NanoSail-D: The Small Satellite That Could," 25th Annual AIAA/USU Conference on Small Satellites, Ogden, UT, 2011.

[5] R. Burton *et al.,* "Initial Development of the CubeSail/UltraSail Spacecraft," Joint Army Navy NASA Air Force (JANNAF) Spacecraft Propulsion Subcommittee Meeting, Colorado Springs, CO, 2010.

[6] S. Bailey, and R. Raffaelle, "Space solar cells and arrays," *Handbook of Photovoltaic Science and Engineering*, 2003, pp. 413-448.

[7] B. Rory *et al.,* "Development of a passively deployed roll-out solar array," 2006.

[8] B. Spence *et al.,* "Next generation ultraflex solar array for NASA's New Millennium Program Space Technology 8," in Editor (Ed.)^(Eds.): "Book Next generation ultraflex solar array for NASA's New Millennium Program Space Technology 8," *IEEE*, 2005, edn., pp. 824-836.

[9] D. Manzella and K. Hack, "High-Power Solar Electric Propulsion for Future NASA Missions," 2014.

[10] E.J. Simburger *et al.,* "Thin-film technology development for the PowerSphere," *Materials Science and Engineering: B*, 2005, 116, (3), pp. 265-272.

11] P. Malone, L. Crawford, and G. Williams, "Developing an inflatable solar array", 1993.

[12] M.L. Breen *et al.,* "IBIS (Integrated Blanket/Interconnect System), Boeing's solution for implementing IMM (Inverted Metamorphic) solar cells on a light-weight flexible solar panel," in Editor (Ed.)^(Eds.): "Book IBIS (Integrated Blanket/Interconnect System), Boeing's solution for implementing IMM (Inverted Metamorphic) solar cells on a light-weight flexible solar panel," *IEEE*, 2010, edn., pp. 000723-000724.

[13] J.W. Zuckermandel, S. Enger, and N. Gupta, "Design, build, and testing of TacSat thin film solar arrays," in Editor (Ed.)^(Eds.): "Book Design, build, and testing of TacSat thin film solar arrays" pp. 29, 2006.

[14] J.A. Carr *et al.,* "The Lightweight Integrated Solar Array and Transceiver (LISA-T): second generation advancements and the future of SmallSat power generation," 2016.

BIOGRAPHY

Les Johnson received a B.A. in Chemistry and Physics from Transylvania University in 1984 and an M.S. in Physics from Vanderbilt University in 1986. Les is the Technical Assistant for NASA's Advanced Concepts Office at the George C. Marshall Space Flight Center and serves as the Co-PI (Solar Sail PI) for the NASA Near-Earth Asteroid Scout mission and Co-Investigator for the European InflateSail solar sail demonstration mission. He thrice received NASA's Exceptional Achievement Medal and has 3 patents. He is also the co-author of the science fiction novel, On to the Asteroid, released in August 2016.

John Carr received a B.S. (2006), M.S. (2010), and Ph.D. (2014) in Electrical Engineering from Iowa State University. John is a power systems engineer in the Space Systems Department at NASA's George C. Marshall Space Flight Center and the technology development lead for the LISA-T project.

Darren Boyd received a received a B.S. (1999) and M.S. (2014) in Electrical Engineering from the University of Kentucky. Darren is a data systems engineer in the Space Systems Department at NASA's George C. Marshall Space Flight Center. He is the RF lead and agile engineering scrum master for the LISA-T project.