Embedded Sail Antenna Technology for Enhanced Sailing and Beyond

Scope Description:

The Mars Cube One (MarCO) mission demonstrated the potential of SmallSat spacecraft to perform interplanetary missions. NASA’s Space Technology Mission Directorate (STMD) and Science Mission Directorate (SMD) are continuing to invest in technologies and interplanetary missions due to the high science value enabled by SmallSat spacecraft; several of those being solar-sail-based missions. However, MarCO was extremely limited in communication rates. Also, future interplanetary missions will be carrying science instrumentation with higher data requirements. This solicitation is seeking deployable embedded technology solutions for large aperture and higher gain, enabling higher data rate communications for interplanetary small spacecraft with an emphasis on applicability to solar sail missions (very low SWaP-C (size, weight, power, and cost)). In particular, gossamer technologies are of interest—both printed and touch labor designs as well as both fixed and electronically steerable. The Near-Earth Asteroid Scout (NEAScout) solar sail architecture can be used as a sample gossamer design reference for the proposed technologies. However, the proposed technologies should be extensible to solar sails in general (i.e., not be tied to NEAScout-specific requirements) as well as to stand-alone devices (i.e., to be applicable to nonsolar sail missions).

Requirements:

- Frequency band: X, Ka, K
- Gain: scalable from ~30 to >50 dBi
- Specific mass: >185 dBi/kg
- Deployable, highly stowable (specific volume dBi/m\(^3\) is to be determined as mission applications progress)

Expected TRL or TRL Range at completion of the Project:

2 to 5
Primary Technology Taxonomy:
Level 1: TX 05 Communications, Navigation, and Orbital Debris Tracking and Characterization Systems
Level 2: TX 05.5 Revolutionary Communications Technologies

Desired Deliverables of Phase I and Phase II:

- Research
- Analysis
- Prototype
- Hardware

Desired Deliverables Description:
The anticipated Phase I product would be a proof-of-concept demonstration of the technology with determination of the Key Performance Parameters by test and/or analyses leading to a higher fidelity prototype(s) and relevant environmental demonstrations in Phase II.

State of the Art and Critical Gaps:
The current state of the art for SmallSat/CubeSat missions is led by ISARA (Integrated Solar Array and Reflectarray Antenna) flown on MarCO. Using a combination reflectarray and patch array, it demonstrated an 8-kbps X-band downlink from Mars orbit with a 28-dB-gain design in a small form factor of <1 kg and 272 cm$^3$ at 5 W. For reference, the Mars Reconnaissance Orbiter is a large spacecraft communicating from approximately the same distance as MarCO with a 46.7-dB 3-m dish that varies from 500- to 4,000-kbps X-band downlink at 100 W.

Outside of ISARA, various arrays of 16 patch antennas or fewer are available from places like Endurosat and Clyde Space with gains from 11.5 to 16 dB. Thin-film solutions such as the Lightweight Integrated Solar Array and anTenna (LISA-T) are in development. However, the ultimate scalability (mechanically, mass, stowage volume, etc.) is limited. Thus, a critical technology gap exists in higher data rate communication solutions for SmallSats outside Earth orbit. The current NASA Small Spacecraft Strategic Technology Plan states this need in several ways including large deployable apertures. This gap is especially critical for deployable solar sail missions such as interstellar probe and potentially for second- and third-generation space weather monitoring platforms. In short, low SWaP-C, high-gain communication techniques that will push small spacecraft data rates towards their larger spacecraft brothers and sisters are needed. To enhance future solar sail missions, these concepts should be amenable if not directly embedded onto the solar sail itself.

Relevance / Science Traceability:
The Small Innovative Missions for Planetary Exploration (SIMPLEx) solicitation opportunities would benefit significantly from higher data rate communication solutions for SmallSat missions. Further specific solar sail missions such as the High-Inclination Solar Polar Image mission and second- and third-generation space weather monitoring missions would be enhanced by this technology, and specific solar sail missions such as the interstellar probe would be enabled by this technology.

References:

2. LISA-T: [https://docs.google.com/viewer?a=v&pid=sites&srcid=ZGVmYXVsdGRvbWFpbnxqb2huYW50aG9ueWNhcnu8Z3g6YzcxMGZjY2Y4MDYwMmJl](https://docs.google.com/viewer?a=v&pid=sites&srcid=ZGVmYXVsdGRvbWFpbnxqb2huYW50aG9ueWNhcnu8Z3g6YzcxMGZjY2Y4MDYwMmJl)
Scope Title

Scalable, Low-Mass Sail Attitude Control Technology for Enhanced Sailing

Scope Description

As solar sails continue to grow in size, so is the need for direct, propellantless, sail-embedded methods attitude control of the sail craft. A primary example of this capability is the so-called reflectivity control devices (RCD), which alter their reflectivity in response to an applied voltage. When embedded in a solar sail system (e.g., near the distal end of a boom), useful momentum transfer and more importantly differentials in momentum that transfer between the on and off states can be captured. RCDs were originally demonstrated for solar sailing by the Japan Aerospace Exploration Agency (JAXA) on the IKAROS (Interplanetary Kite-craft Accelerated by Radiation of the Sun) mission and are currently being further developed by NASA in the Solar Cruiser program. As sails are scaled beyond the Solar Cruiser class and taken into more and more extreme environments, stronger and more robust sail-embedded attitude control devices will be needed. More specifically, devices that can provide greater "on-to-off ratios" (greater attitude control) while utilizing less power and surviving a broader, more extreme temperature range are needed.

Key Performance Parameters:

1. Consider two sail point designs, consisting of two areas and two masses (0.12 mm/sec2, 0.24 mm/sec2):
   - Area1 = 1650 m², Mass1 = 115 kg
   - Area1 = 7000 m², Mass2 = 240 kg

2. Mass of the solution should not exceed 3% of sail mass (3.45 kg, 7.2 kg).
3. Torque as a function of SIA meeting or exceeding the following:

<table>
<thead>
<tr>
<th>Case</th>
<th>Out-of-Plane (Roll) Torque [N-m]</th>
<th>In-Plane (Pitch/Yaw) Torque [N-m]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Cruiser (1650 m²) 0° SIA</td>
<td>4.7x10^-6</td>
<td>5.5x10^-4</td>
</tr>
<tr>
<td>Solar Cruiser (1650 m²) 35° SIA</td>
<td>4.9x10^-5</td>
<td>2.4x10^-3</td>
</tr>
<tr>
<td>SPI (7000 m²) 0° SIA</td>
<td>7.7x10^-5</td>
<td>4.6x10^-3</td>
</tr>
<tr>
<td>SPI (7000 m²) 17° SIA</td>
<td>6.4x10^-4</td>
<td>4.7x10^-2</td>
</tr>
</tbody>
</table>

4. Power requirements (if any) should also be defined as a part of the proposed solution.
5. Assessment of space environmental survivability—especially for expected temperature survivability (large range of hot-cold survivability is needed).

Expected TRL or TRL Range at completion of the Project: 2 to 5

Primary Technology Taxonomy:
Level 1: TX 01 Propulsion Systems
Level 2: TX 01.4 Advanced Propulsion

Desired Deliverables of Phase I and Phase II:
- Research
**Desired Deliverables Description:**

The anticipated Phase I product of this solicitation would be a proof-of-concept demonstration of the technology with determination of the Key Performance Parameters by test and/or analyses leading to a higher fidelity prototype(s) and relevant environmental demonstrations in Phase II.

**State of the Art and Critical Gaps:**

The current state of the art for embedded attitude control devices are defined by RCDs developed by JAXA (see references) as well as Dakang Ma et al. (in partnership with NASA). These “first-generation” devices are being advanced to second generation by both NASA and industry; however, results have not been published. These devices are appropriate for medium-class solar sail missions (e.g., <1600 m²). Advanced devices would be enhancing for this class and potentially enabling for scaling to large class sails (e.g., >7000 m²) as well as for sails that will travel into more extremes environments (e.g., hot or cold cases).

**Relevance / Science Traceability:**

Large-class solar sails (e.g., >7000 m²) are important in achieving not currently possible heliophysics missions such as the High Inclination Solar Imaging missions as well as significantly enhancing for fast transit to deeper space, which is needed for the Interstellar Probe mission.

**References:**

2. Hirokazu Ishida, et al.: Optimal Design of Advanced Reflectivity Control Device for Solar Sails Considering Polarization Properties of Liquid Crystal, [https://www.semanticscholar.org/paper/Optimal-Design-of-Advanced-Reflectivity-Control-for-Hirokazu-Sh%C3%ADd%C3%A0/cfbc675862ca232e0d52b5cfd0173ffcc969d7c7c](https://www.semanticscholar.org/paper/Optimal-Design-of-Advanced-Reflectivity-Control-for-Hirokazu-Sh%C3%ADd%C3%A0/cfbc675862ca232e0d52b5cfd0173ffcc969d7c7c)

**Scope Title**

Next-Generation Solar Sail System Technologies for Enhanced and Enabling Sailing

**Scope Description**

Aside from the two targeted scope technologies within this subtopic, NASA also recognizes there are several new and budding ideas that may prove to be significantly enhancing or enabling for next-generation (post Solar Cruiser) sailing. In this scope, ideas for advanced technologies in the core categories of advanced sail materials (especially diffractive and metamaterials), advanced sail deployment booms, and sail-embedded power-generation concepts (especially ultraviolet (UV) stable thin-film protective coatings) are solicited. Direct requirements nor key performance parameters in these categories are not being solicited; however, offerors must quantitatively compare their concepts to state-of-the-art sailing technologies and clearly show how the offered technology is expected to be significantly enhancing or enabling to the next generation of solar sails.

**Expected TRL or TRL Range at completion of the Project**

2 to 5

**Primary Technology Taxonomy**
Desired Deliverables of Phase I and Phase II

- Research
- Analysis
- Prototype

Desired Deliverables Description

The anticipated Phase I product of this solicitation would be a proof-of-concept demonstration of the technology with determination of the Key Performance Parameters by test and/or analyses leading to a higher fidelity prototype(s) and relevant environmental demonstrations in Phase II.

State of the Art and Critical Gaps

Gaps within advanced sail material, advanced boom and deployers, as well as embedded power generation exist for larger (larger than solar cruiser) class sails—such as those proposed for the HISM (High Inclination Solar Mission) and SPI (Solar Polar Imager) missions. State-of-the-art sail materials used on NEA Scout and Solar Cruiser are CP1 (colorless polyimide 1). Lighter materials with higher photon momentum transfer are highly enhancing. State-of-the-art booms are composite based and typically are a "TRAC" (Triangular Rollable and Collapsible). Improved mass and strength properties are both enhancing and enabling. State-of-the-art embedded power generation is based on LISA (Lightweight Integrated Solar Array) and LISA-T (Lightweight Integrated Solar Array and anTenna) concepts. UV robust coatings provided greater radiation protection without sacrificing mass and thickness, and flexibility would be both enhancing and enabling.

Relevance / Science Traceability

Next-generation solar sailing will enable several priority sciences missions such as out of the ecliptic plane imaging of the Sun as well as fast transit to deep space for the interstellar probe.

References


