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## Letter to the Editor

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### *A Solar-powered Outer Solar System SmallSat (OS4) Architecture Defined*

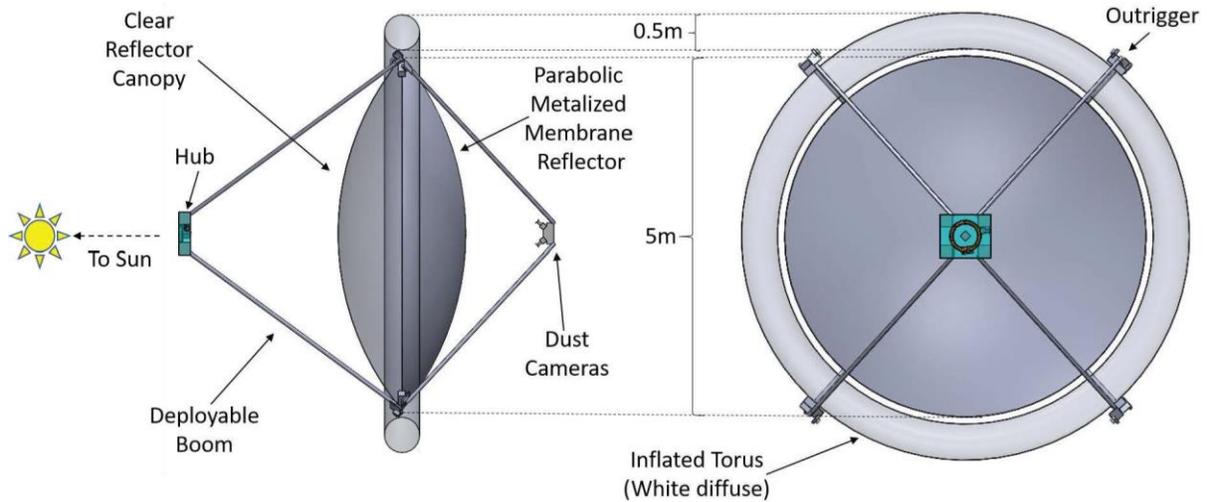
Dear Editor,

To date, all spacecraft going beyond the orbit of Jupiter have required dedicated launch vehicles, radioisotopes for electrical power and heat, and dozens or more of ground operations staff. As result, all such missions have been large and expensive, though they have clearly produced major scientific advances. In a NASA Innovative Advanced Concepts (NIAC) Phase 1 task performed in 2019–2020, our team has defined an approach and technology path to enable SmallSats with solar-only power to explore multiple portions of the Solar System between the orbits of Jupiter and Neptune, and potentially far beyond<sup>1</sup>, starting in the next decade. With achievable developments in low-power electronics, thermal control, cold-tolerant equipment, rigidized inflatable structures, and longer-life pulsed-plasma thrusters, such spacecraft using rideshare launches aboard primary missions could carry a variety of instruments for heliophysics, small-body, and planetary measurements. Originally conceived as a method for reaching the heliopause with magnetometer, plasma, energetic particle and dust instruments, a smaller version of the concept was defined for operations to 30 AU (Neptune’s orbit), capable of carrying cameras and spectrometers as well. A larger version, no longer a “SmallSat,” would be needed to collect enough sunlight to operate beyond the heliopause distance of ~120 AU. Our investigation has shown the feasibility at Technology Readiness Level (TRL) 2 for SmallSats compatible with the family of Evolved expendable launch vehicle Secondary Payload Adapters (ESPA). Operation to perhaps twice Neptune’s solar distance may be possible with an upgraded thermal insulation approach.

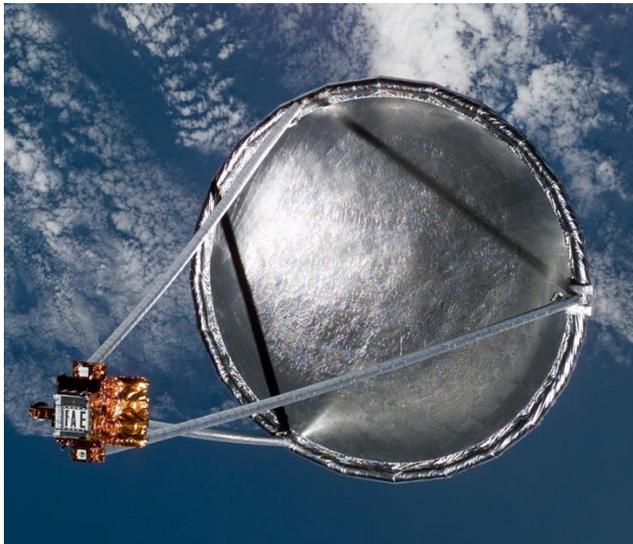
Based on the results of our NIAC Phase I work, we outline a new architecture that could enable many outer Solar System SmallSat (OS4) mission concepts at 1/10th the cost and mass, and 1–2% of the equivalent continuous power level and operations staffing typically required of such missions. Inspired by the CubeSat revolution in small, low power electronics and miniature instruments, it appears that a small enough mass and launch size is achievable such that these Outer Solar System (OSS) explorers could be launched as secondary payloads along with primary missions to the OSS, such as those to Europa and farther (e.g., New Frontiers Round 6 or 7 selections), and use Jupiter swing-bys to target different destinations.

These SmallSats would ride independently of the primary mission, as the MarCOs (Mars Cube One A & B) did with InSight (Interior Exploration using Seismic Investigations, Geodesy and Heat Transport). The SmallSat(s) would then separate from the launch vehicle and maneuver to their own Jupiter fly-by that could be used to target different destinations in the OSS.

While we show many elements of an “existence proof-level” design for an example mission in our full report (available at: [https://www.nasa.gov/sites/default/files/atoms/files/niac\\_2019\\_phi\\_staeble\\_os4\\_tagged.pdf](https://www.nasa.gov/sites/default/files/atoms/files/niac_2019_phi_staeble_os4_tagged.pdf); also on the NIAC website at: [https://www.nasa.gov/directorates/spacetech/niac/2019\\_Phase\\_I\\_Phase\\_II/Low\\_Cost\\_SmallSats/](https://www.nasa.gov/directorates/spacetech/niac/2019_Phase_I_Phase_II/Low_Cost_SmallSats/)), we note that this design is not complete, and far from optimal. We believe that no laws of physics need be violated, and that all required technology improvements are achievable over the next decade within the limits of modest expenditure, and/or their achievement will be motivated by uses and rationale beyond enabling Outer Solar System SmallSats.



Outer Solar System SmallSat (OS4; ~220 kg total) spacecraft concept cross-section (left) of 5 m diameter inflated paraboloid reflector and clear canopy, suspended within a Torus providing tension for structural stability. A Hub, or bus is located so that solar cells cover an area near the focus of the Parabolic Metalized Membrane Reflector to intercept nearly all of the sunlight beyond ~6 AU. From 1 – ~6 AU, the spin axis is pointed off-Sun to reduce heat loading. Beyond 6 AU the spin axis (“To Sun” in left figure) points to the Sun. Periods of Earth pointing enable telecommunications. RF waves pass through a transparent Fresnel Element (not shown) between the Hub and the Clear Reflector Canopy that uses refraction to diffuse visible wave-lengths onto a concentrated solar panel on the anti-Sun side of the Hub. Attitude/trajectory correction maneuver (TCM) thrusters are in Outriggers on the ends of the four Deployable Booms. Right side is view from sunward side along spin axis.



The inflatables portion of the architecture is evolved from the partially-successful Shuttle-borne 1997 Spartan-207 flight demonstration of a 14-meter reflector managed by JPL. (Photo: NASA) On the right, this sub-scale ground version of the Spartan-207 hardware is approximately the 5-meter diameter specified for the OS4 concept. (Photo: NASA/JPL-Caltech/L'Garde)

Key drivers of the architecture include:

- *Energy:* If one assumes a 5-m parabolic reflector diameter, then electrical output at 30 AU would be 4 W, assuming low-intensity low-temperature (LILT) solar cells<sup>ii</sup> covering a concentrated area of 0.3 m<sup>2</sup> could operate at adequate temperature, accounting for the efficiency chain from raw sunlight to electrical power.
- *Telecommunications:* Using standard Deep Space Network (DSN) parameters, 5 m diameter reflective surface aperture, X-band to 34 m DSN station yields 3 kbps at 30 AU for 20 W rf transmit power. Scheduled transmissions can be performed at a low duty cycle from a few hours per week to 1 hr/month. For heliophysics-focused missions with no specific destination, a downlink-only mission appears viable after navigating to a Jupiter swing-by that targets escape direction to a particular sector of the outer Solar System. When a specific Solar System body destination is a mission focus, then a standard uplink/downlink mission is envisaged.
- *Structure:* Inflatable structures have been flown in space since Echo 1 in 1960.<sup>iii</sup> Recent work on inflatable high gain antennas has been performed at JPL and ASU, testing inflation of parabolic antennae.<sup>iv</sup> UV rigidization has been explored in this and prior work, so that pressure need not be retained.<sup>v</sup> Ribs built into gores of a paraboloid on the ground can be filled with a liquid that rigidizes in solar UV. Our configuration incorporated key elements of the Spartan 207 technology demonstration deployed in 1997 from the Space Shuttle.<sup>vi</sup>
- *Autonomy:* After launch and Jupiter fly-by, mission operations could be vastly simplified. With few modes, and “smart” instrumentation, some subsystems will be “asleep” to save power >90% of the time. On Solar System escape trajectories, attitude changes required to maintain Earth pointing are modest. Rather than downlinking raw data, instrument data could be processed onboard while raw data is stored, with the possibility of downlinking selected very small segments of raw data to verify onboard processing techniques. Full autonomy of this operations concept is well within flight proven technology, such as demonstrated with the Autonomous Sciencecraft Experiment aboard Earth Observing One (EO-1).<sup>vii</sup>
- *Launch availability:* Any mission going to the Jovian system as either a destination or trajectory waypoint is likely to have 100s of kg of launch mass margin, which could accommodate one or a few OS4s as secondary payloads.
- *Instrumentation:* A magnetometer being developed at JPL was incorporated into the example mission design.<sup>viii</sup> Two charged-particle instruments from SwRI were also incorporated into the example mission design for heliophysics measurements: a) the Solar Wind Ion & Electron Sensor (IES) based on the *Rosetta* instrument and b) the Miniaturized Electron and Ion Telescope (MeRIT) for higher-energy charged particles. One dust-measuring instrument concept was incorporated into the example design, taking advantage of the large cross section of the Parabolic Metalized Membrane Reflector (PMMR). Feasibility of other instrumentation, e.g., for galactic cosmic rays (GCRs) and anomalous cosmic rays (ACRs), could be considered.<sup>ix</sup> Finally, a Solar System Portrait Camera was incorporated more for the artistic, educational, and recording-for-posterity value than its likely scientific yield.
- *Lifetime:* The *Voyagers and Pioneers* demonstrate that multi-decade lifetimes are possible. Several generations of electronics later, it is worth noting that some modern CMOS electronics has proven space-worthy and rad-tolerant at relevant levels, especially deeply-scaled CMOS technology (smaller than 65 nm) where the surface quality of nanometer transistors creates high robustness to total ionized dose (TID) through fewer trapped charges, and better single event rejection from a much-reduced transistor cross section area.<sup>x</sup> Emerging CMOS System-on-a-Chip (SoC) technology has the ability to

co-integrate digital, analog, mixed-signal (analog and digital), memory, and rf circuitry all together on a single chip. This capability provides a pathway to build all spaceborne electronics as a single SoC.

In the case of missions envisaged to Neptune's orbital distance, mission times of 10–15 years are likely to be the norm. Therefore, while recognizing the likely advancements cited above, our example mission employs a set of electronics available and in development today that has sufficient capability, with dramatically lower power draw than typically used in spacecraft today.

We did not investigate the cost of our example mission. However, applying the SmallSat paradigm and typical cost-per-kg values, a target cost of FY2020 \$50 M each for multiple units to be launched ~2030 appears reasonable. If that were to prove true, then significant numbers of OS4s (e.g., 6 to 12, spread among different launch opportunities) could be launched onto multiple escape trajectories to provide a truly multidirectional view of the interplanetary medium, and to fly by and take measurements at a selection of outer Solar System destinations. Within the 30 AU heliocentric distance capability of the probes, measurements by each probe, coupled with those taken in the inner Solar System from other platforms, could go a long way toward completing our understanding of how the solar wind propagates in all directions, throughout the solar cycle, by comparing the measurements from different probes at similar distances in different directions from the Sun, adding to measurements we have from missions to date. With a minimum set of six OS4s targeted to Solar System escape in different directions spaced around the heliosphere, the magnetic field, plasma, and dust environment could be mapped across the volume of our Solar System to a distance represented by the orbit of Neptune, and potentially beyond.

To implement OS4s, technology advancements are required in the disciplines of 1) cold-tolerant equipment, 2) inflatables, 3) attitude sensing, and 4) longer-life and low operating temperature pulsed-plasma thrusters. A three-axis stabilized implementation may be possible, wherein no advancement in attitude sensing technology would be needed. Other advancements could be helpful beyond these. Advancements already motivated for other reasons, e.g., in space-capable low-power electronics and artificial intelligence software, would clearly be incorporated into any maturing design.

Once the basic technology is developed for OSS SmallSats, it is probable that other institutions and countries will want to “join the club” of those exploring the outer Solar System, just as new-to-space universities and nations have in the last two decades made the financial and intellectual investments to build CubeSats, and even mount missions to the Moon and Mars. As with Interplanetary CubeSats,<sup>xi</sup> OS4s would lower the barriers to performing serious science investigations at multiple destinations.

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<sup>i</sup> Kian Crowley (2018): “Exploring the Concept of a Deep Space Solar-Powered Small Satellite,” [considering feasibility at 100 AU], Master’s Thesis, Aerospace Engineering, California Polytechnic State University, San Luis Obispo, CA US. [Prof. Jordi Puig-Suari (concept originator) and Robert Staehle (PI) served as thesis advisors.]

<sup>ii</sup> Andreea Boca, J. Grandidier, Claiborne McPheeters, Paul Sharps, Philip Chiu, Xing-Quan Liu, James Ermer (2017): *Advanced-Architecture High-Efficiency Solar Cells for Low Irradiance Low Temperature (LILT) Applications*, NASA Jet Propulsion Laboratory; and Andreea Boca, Paul Stella, Christopher Kerestes, Paul Sharps (2017): *Solar Arrays for Low-Irradiance Low-Temperature and High-Radiation Environment*, NASA Jet Propulsion Laboratory. Available at: <https://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/20170010685.pdf>

<sup>iii</sup> 68 kg, 30.5 m diameter, as in *Explorer/Early Satellites: Project Echo* (2011): NASA Langley Research Center. Available at: <https://www.nasa.gov/centers/langley/about/project-echo.html>

<sup>iv</sup> Alessandra Babuscia, Jonathan Sauder, Aman Chandra, Jekan Thangavelautham, Lorenzo Feruglio and Nicole Bienert (2017): “Inflatable Antenna for CubeSat: A New Spherical Design for Increased X-band Gain,” in *Proc. 2017 IEEE Aerospace Conf.*, Big Sky, MT, pp. 1-10. doi: 10.1109/AERO.2017.7943897. Available at: <http://ieeexplore.ieee.org/stamp/stamp.jsp?tp=&arnumber=7943897&isnumber=7943554>

<sup>v</sup> R. Gilbert Moore (1990): “Apparatus for Foaming Bubbles,” *U.S. Patent Number 4,961,699*, October 9.

<sup>vi</sup> Arthur B. Chmielewski (2020, January): Personal communication to Robert Staehle, having been JPL program manager overseeing the Spartan 207 technology demonstration project. This contact was made after NIAC Fellow Joel Sercel’s personal communication to Robert Staehle in September 2019 concerning the capability he was aware of by one or more employees at L’Garde Inc., Tustin, CA to calculate, cut, and bond gores of the proper shape.

<sup>vii</sup> Chien, S., Sherwood, R., Tran, D., Cichy, B., Rabideau, G., Castano, R., Davies, A., Mandl, D.; Frye, S., Trout, B., Shulman, S., and Boyer, D. (2005): [Using Autonomy Flight Software to Improve Science Return on Earth Observing One](#). *J. of Aerospace Computing, Information, and Communication (JACIC)*, April, pp. 196–216.

<sup>viii</sup> Corey J. Cochrane, Jordana Blacksberg, Mark A. Anders, and Patrick M. Lenahan (2016): “Vectorized Magnetometer for Space Applications Using Electrical Readout of Atomic Scale Defects in Silicon Carbide,” *Scientific Reports* 6, 37077. doi: 10.1038/srep37077. Available at: <https://www.nature.com/articles/srep37077>

<sup>ix</sup> Martin H. Israel et al. (2011): *The Effect of the Heliosphere on Galactic and Anomalous Cosmic Rays*, Washington University White Paper for Solar and Heliospheric Physics (SHP) Panel. Available at: [http://www8.nationalacademies.org/SSBSurvey/DetailFileDisplay.aspx?id=688&parm\\_type=HDS](http://www8.nationalacademies.org/SSBSurvey/DetailFileDisplay.aspx?id=688&parm_type=HDS)

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<sup>x</sup> Adrian Tang, Yangyho Kim, Mau-Chung Frank Chang (2016): "Logic-I/O Threshold Comparing Gamma Radiation Dosimeter in Insensitive Deep-Sub-Micron CMOS," *IEEE Trans. on Nuclear Science*, Vol. 63, No. 2, pp. 1247–1250. Available at: <https://ieeexplore.ieee.org/document/7454832>

<sup>xi</sup> Robert L. Staehle, Diana Blaney, Hamid Hemmati, Dayton Jones, Andrew Klesh, Paulett Liewer, Joseph Lazio, Martin Wen-Yu Lo, Pantazis Mouroulis, Neil Murphy, Paula J. Pingree, Thor Wilson, Brian Anderson, C. Channing Chow II, Bruce Betts, Louis Friedman, Jordi Puig-Suari, Austin Williams, and Tomas Svitek (2013): "Interplanetary CubeSats: Opening the Solar System to a Broad Community at Lower Cost", *J. of Small Satellites (JoSS)*, Vol. 2, No. 1, pp. 161–186. Available at: <http://23.235.211.190/~jossonline/wp-content/uploads/2014/12/0201-Interplanetary-CubeSats-Opening-the-Solar-System-to-a-Broad-Community-at-Lower-Cost.pdf>