

**The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) CubeSat  
Mission: A Pathfinder for a New Measurement of Earth's Radiation Budget**

William H. Swartz  
Johns Hopkins University Applied Physics Laboratory  
11100 Johns Hopkins Road, Laurel, MD 20723; 240-228-8462  
bill.swartz@jhuapl.edu

Steven R. Lorentz  
L-1 Standards and Technology  
209 High Street, New Windsor, MD 21776; 410-635-3300  
lorentz@l-1.biz

Philip M. Huang  
Johns Hopkins University Applied Physics Laboratory  
11100 Johns Hopkins Road, Laurel, MD 20723; 240-228-6461  
philip.huang@jhuapl.edu

Allan W. Smith  
L-1 Standards and Technology  
209 High Street, New Windsor, MD 21776; 410-635-3300  
allan.smith@l-1.biz

David M. Deglau, Shawn X. Liang, Kathryn M. Marcotte, Edward L. Reynolds, and Stergios J. Papadakis  
Johns Hopkins University Applied Physics Laboratory  
11100 Johns Hopkins Road, Laurel, MD 20723; 240-228-9307  
david.deglau@jhuapl.edu

Lars P. Dyrud  
OmniEarth  
251 18th Street South, Suite 650, Arlington, VA 22202; 888-838-6318  
lars.dyrud@omniearth.net

Dong L. Wu and Warren J. Wiscombe  
NASA Goddard Space Flight Center  
8800 Greenbelt Road, Greenbelt, MD 20771; 301-614-5784  
dong.l.wu@nasa.gov

John Carvo  
Blue Canyon Technologies  
2425 55<sup>th</sup> St. Suite A-200, Boulder, CO 80301; 720-573-6492  
jcarvo@bluecanyontech.com

**ABSTRACT**

The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) mission is a 3U CubeSat pathfinder for a constellation to measure the Earth's radiation imbalance (ERI), which is the single most important quantity for predicting the course of climate change over the next century. RAVAN will demonstrate a small, accurate radiometer that measures top-of-the-atmosphere Earth-leaving fluxes of total and solar-reflected radiation. RAVAN demonstrates two key enabling technologies. The first is the use of vertically aligned carbon nanotubes (VACNTs) as a radiometer absorber. VACNT forests are some of the blackest materials known and have an extremely flat spectral response over a wide wavelength range. The second key technology is a gallium fixed-point black body calibration source, which serves as a stable and repeatable reference to track the long-term degradation of the sensor.

Absolute calibration is maintained by regular solar and deep space views. The RAVAN payload will fly on a 3U CubeSat that combines stellar attitude determination, sub-degree pointing, and both UHF and Globalstar communication. RAVAN will help enable the development of an Earth radiation budget constellation mission that can provide the measurements needed for superior predictions of future climate change.

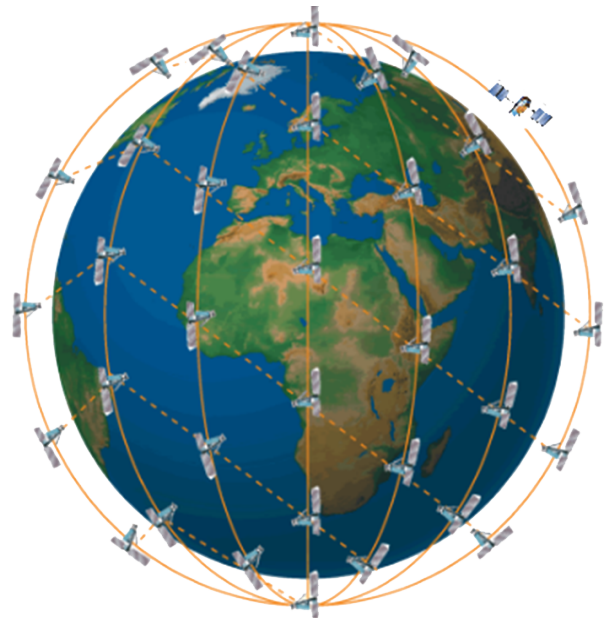
## SCIENCE MOTIVATION

Our ability to understand and predict Earth's future climate is limited by our ability to track energy within the Earth system.<sup>1</sup> Climate change is driven by changes in Earth's global energy budget resulting from a very small yet important imbalance between the incoming solar energy reaching the Earth system and the outgoing solar-reflected and thermally emitted radiation. The Earth radiation imbalance (ERI) is the single most important number for predicting the course of climate change over the next century.<sup>1,2</sup> If ERI is negative, meaning the Earth radiates more energy than it absorbs, Earth will cool. If ERI is positive, Earth will warm as energy accumulates in the atmosphere and oceans. Current research suggests that ERI is on the order of +1 W/m<sup>2</sup> on an annual global mean basis in the current epoch (meaning that the outgoing radiation is less than the incoming solar radiation by about 0.3%), based on the combination of satellite observations, ocean heat content measurements, meteorological re-analyses, and models. The imbalance is a result of the net effect of anthropogenic emissions of greenhouse gases and aerosols.<sup>3</sup> Accurately measuring ERI would help resolve the current ambiguity between aerosols and ocean down-mixing as the cause of the recent apparent global warming slowdown and would improve the projection of future climate by climate models.

Although long-term climate shifts are forced in part by changes in solar activity and Earth's orbit, the incoming solar energy in recent decades is known to have been quite stable, with only small-amplitude (<0.1%) solar cycle variations.<sup>4</sup> Further, the incoming solar irradiance has been quantified precisely from space: 340.20±0.12 W/m<sup>2</sup> (global average integrated over the top of the atmosphere) during the most recent solar minimum.<sup>5</sup>

The challenge in measuring ERI therefore lies in the measurement of the total outgoing radiation (TOR). Unlike the solar irradiance, which can be measured very precisely with single-point space-based observations, TOR fluctuates across the Earth rapidly, for example with weather variability<sup>6</sup> and the El Niño/La Niña–Southern Oscillation (ENSO).<sup>7</sup> The value of the annual, globally averaged ERI derived from satellite-only observations<sup>8</sup> ranges from –2 to +7 W/m<sup>2</sup>—much larger than the +1 W/m<sup>2</sup> value of ERI currently suspected. Observations of TOR with an accuracy to within about 0.5 W/m<sup>2</sup> are therefore needed to resolve the value of ERI.

Two key goals lie at the frontier of climate observation from space: (1) global measurement of the Earth radiation diurnal cycle at accuracies commensurate with the global imbalance and (2) measurement of ERI as a global synoptic constraint of the predictions of climate models. To achieve these challenging goals, a new approach to the Earth radiation budget is needed.<sup>9</sup> ERI is too small to be measured definitively by previous and current space assets, due in part to temporal and spatial coverage that does not capture the system's inherent and rapid variability; further, there has heretofore been a reliance on climate model calculations, making it difficult to come to closure on the Earth radiation budget.



**Figure 1: Earth radiation budget constellation making definitive measurement of the radiation imbalance and its diurnal variation. RAVAN demonstrates technologies that would enable such a constellation.**

The maturation of small satellites, hosted payloads, and constellation technologies provides a unique and timely opportunity for making the next great leap in Earth radiation budget measurement.<sup>10</sup> What is needed is a space-based analog of the Argo ocean observation network: a constellation of compact, spaceborne radiometers that are absolutely accurate to NIST-traceable standards and that can be affordably built in quantities of 40 or more (Figure 1). Such a constellation would enable accurate, un-tuned measurements of ERI

with the diurnal and multi-directional sampling needed to capture spatiotemporal variations in clouds, surfaces, natural and anthropogenic aerosols and gases, vegetation, and photochemical phenomena.

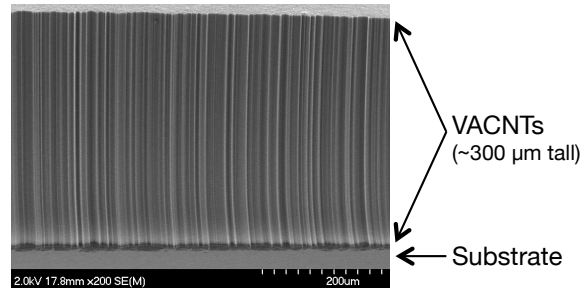
Before an Earth radiation budget constellation exploiting hosted payloads or inexpensive small satellites can be realized, it is necessary to build and fly a compact radiometer that captures all outgoing radiation from the ultraviolet (200 nm) to the far infrared (200  $\mu\text{m}$ ) with climate accuracy (better than 0.5  $\text{W}/\text{m}^2$  absolute). Further, we have to show that the accuracy standard remains stable over time on orbit and that such a radiometer is possible at low cost. These are the challenges RAVAN addresses.

### TECHNOLOGIES DEMONSTRATED

The RAVAN project is funded by the NASA Earth Science Technology Office’s In-Space Validation of Earth Science Technologies (InVEST) program as a pathfinder for a possible future Earth radiation budget constellation mission. RAVAN will demonstrate on a 3U CubeSat two key technologies that enable accurate, absolute Earth radiation measurements using a remarkably small instrument: radiometers with vertically aligned carbon nanotube (VACNT) absorbers and gallium black body phase-transition calibration sources.

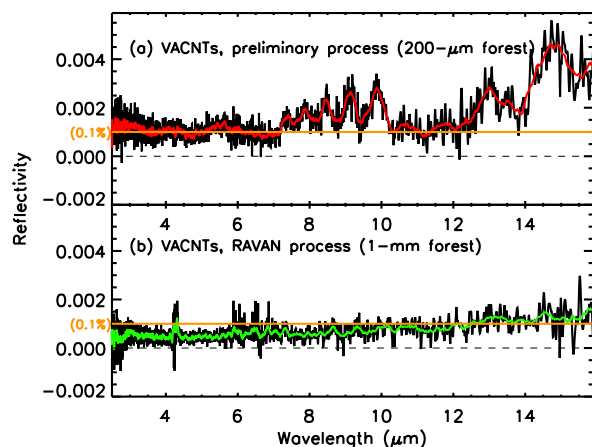
#### *Vertically Aligned Carbon Nanotubes as Radiometer Absorbers*

Carbon nanotubes are an allotrope of carbon that, at a microscopic level, are essentially long, hollow graphene cylinders.<sup>11</sup> These nanostructures have a number of unusual properties that make them ideal for certain applications. Vertically aligned carbon nanotube “forests” are some of the blackest materials known and have an extremely flat spectral response over a wide wavelength range. VACNTs, as shown in Figure 2, are actually mostly empty space and are highly efficient photon traps. In addition to providing a very good approximation of a black body, their high thermal conductivity suits them well as radiometer absorbers. Further, they are ideal for space-based applications because they are compact, do not outgas, and are mechanically robust.



**Figure 2: Vertically aligned carbon nanotube (VACNT) forest viewed edge-on under a scanning electron microscope. The height of the forest is roughly 300  $\mu\text{m}$ .**

The VACNT forests used in RAVAN were grown at the Johns Hopkins University Applied Physics Laboratory (JHU/APL) using water-assisted chemical vapor deposition with ethylene as the carbon feedstock on silicon wafers covered with an iron catalyst layer. Post-growth vapor modifications and plasma etching were then performed to decrease the material’s reflectivity further. We experimented with a number of processes with varying VACNT forest thickness, single/multiple growths, and a range of post-growth modification severity, in order to optimize the performance for RAVAN. The infrared reflectivity indicative of early experiments and the final RAVAN flight VACNT radiometer absorbers are shown in Figure 3. The RAVAN VACNTs stay below a target 0.1% reflectivity out to about 13  $\mu\text{m}$ . We found agreement with literature techniques<sup>12</sup> that increasing the forest thickness to 1 mm and a more aggressive  $\text{O}_2$  plasma etching post-growth each improved the infrared performance compared to our early experiments.



**Figure 3: Spectral reflectivity of VACNT forests produced with two different processes. Both are single growths, but the latter (b) was grown to a greater thickness (1 mm) and with more aggressive post-growth modification.**

To allay concerns about the potential risk of the VACNT forest separating from the substrate or loss of structural integrity during launch, we performed 3-axis vibration testing on VACNT samples. The tests included sine surveys and random vibrations to NASA General Environmental Verification Standard (GEVS) levels. Overall the samples showed no gross change or irregularity detectable by scanning electron microscopy that would indicate that they would be damaged by the spacecraft launch.

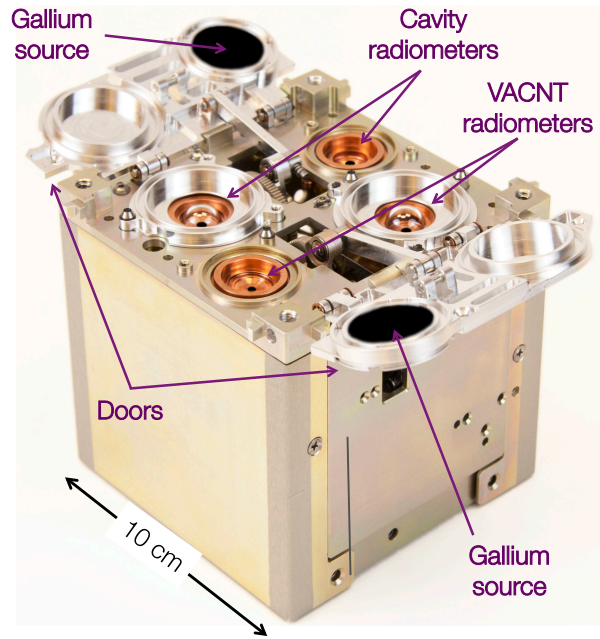
### ***Gallium Black Bodies for On-Board Calibration***

The second key technology is the gallium calibration source. Embedded in RAVAN's sensor head contamination covers (see below, Figure 4) are two gallium fixed-point black bodies that serve as on-orbit infrared sources that, when coupled with deep space looks, provide an additional means to determine the offset for the total channels. The black bodies consist of a high-purity gallium cell located directly over the detector. We use the gallium solid-liquid phase transition (29.76°C) as a stable reference for the black body emission. The calibration sources are used as stable and repeatable references to track the long-term degradation of the radiometer sensors. Gallium is not toxic, and only stable isotopes are used in RAVAN (different than those used in medical imaging), so its presence poses no human risk during spacecraft integration.

## **PAYLOAD**

### ***Design***

We treat measurement of the Earth's outgoing radiation as a simple irradiance measurement using thermal detectors with spectrally flat absorbers and precision apertures. The RAVAN payload, developed with L-1 Standards and Technology, comprises four independent radiometers in two pairs, as shown in Figure 4. The primary pair use VACNT absorbers; the secondary pair use a traditional, conical cavity design, for intercomparison, redundancy, and degradation monitoring. Each pair has a total (Total) channel, measuring all radiation from the ultraviolet (200 nm) to the far infrared (200 μm), and a shortwave (SW) channel, which is limited to wavelengths less than about 5.5 μm by a sapphire dome. The SW channels will allow RAVAN to distinguish between solar-reflected sunlight and the Earth's total emission. The radiometers have a wide field of view (FOV), close to 130°. This is needed so that the entire Earth disk can be viewed from low Earth orbit. Apart from the sapphire domes of the SW channels, there are no optics between the light source and the radiometer absorbers.



**Figure 4: RAVAN flight payload, comprising four independent radiometers: primary pair (VACNT absorbers; total and shortwave channels) and an analogous, secondary pair (cavity absorbers; total and shortwave channels).**

The RAVAN payload has two re-closable doors, actuated by stepper motors, which cover the primary and secondary radiometer pairs. The doors protect the radiometers before launch and during commissioning, and they will be closed as needed during the mission. The gallium black bodies are situated in the doors such that they lie directly over the Total channels when the doors are closed. Incidentally, VACNTs also cover the gallium sources, desirable because of their high emissivity. We used the same growth procedure for these as the radiometer VACNT absorbers.

The radiation sensors themselves are electrical substitution radiometers. In each, thermistors monitor the temperatures of the absorber and heat sink. A bridge circuit senses temperature changes due to light absorption. Electrical heaters in the absorber remove the thermal link, thermistors, and bridge circuit from calibration. Heaters in the heat sink control the temperature of the detectors versus the spacecraft bus. The radiometers are then calibrated for power responsivity, noise floor, aperture area, spectral bandpass, and field of view.

The payload mass is less than 1 kg, draws 1.9 W of power (orbit average), and fits within a 1U volume (<10x10x10 cm<sup>3</sup>). The RAVAN payload will produce approximately 2.5 MB of science and housekeeping data per day.

### Calibration

The absolute calibration requirement for climate accuracy is exceedingly stringent, and to meet this requirement an involved calibration procedure is planned for before launch and during the mission. Before flight, ground calibration includes component-level and end-to-end calibrations that are tied directly to NIST standards. Laser-based measurements will be performed for the SW channels, along with calibration of the Total channels with a ground-based fixed-point gallium black body, which is known to 0.005 K ( $1-\sigma$ , corresponding to  $0.03 \text{ W m}^{-2}$ ).

The principal calibration of RAVAN will occur on orbit, with the Sun as the primary, absolute standard and deep (cold) space characterizing the offset. The integral gallium black body emitters serve as a transfer standard for the Total channels to the pre-launch ground calibration and to monitor degradation of both the primary and secondary Total channels. The various calibration and inter-calibration modes planned are included in Table 1. The calibration procedures will be performed at weekly and monthly intervals (monthly for full calibrations).

**Table 1: Modes of operation**

Mode	Configuration	Purpose
Normal	Nadir, VACNT radiometer doors open	Normal Earth data collection
Solar	Point at Sun, doors open	Absolute calibration
Deep Space	Point at deep space, doors open	Offset calibration
Ga black body	Doors closed	Calibration with gallium black bodies
Inter-calibration	Both doors open	Intercompare VACNT and cavity radiometers

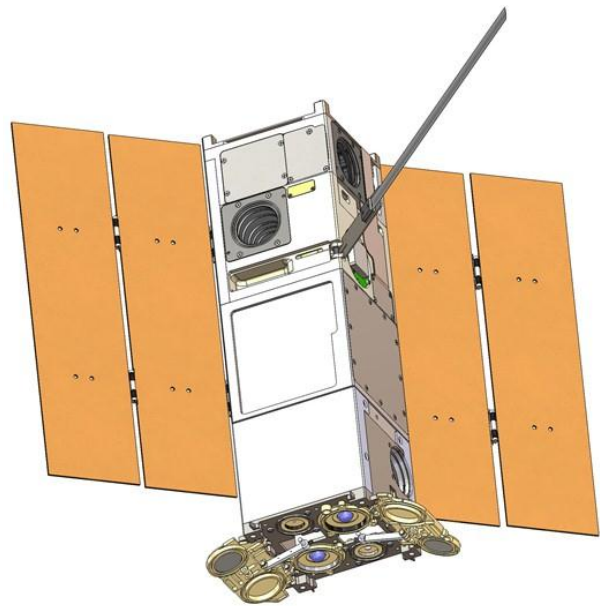
On-orbit nadir-pointing and calibration maneuvers drive the attitude control requirements imposed on the CubeSat bus:  $0.5^\circ$  pointing control;  $0.1^\circ$  pointing knowledge.

### MISSION DESIGN

#### Spacecraft Bus

Although JHU/APL has successfully flown CubeSats in the past and expects to in the future,<sup>13</sup> we determined that the particular requirements of the RAVAN project were more effectively met by partnering with a third party to design, build, and operate the spacecraft. The RAVAN radiometer payload will be hosted on a 3U CubeSat bus designed and built by Blue Canyon Technologies (BCT), based on their XB1 design

(Figure 5). The BCT bus has 3-axis attitude control afforded by three reaction wheels, three magnetic torque rods, and two star trackers, with a GPS receiver for position and time. Power is provided by four deployable solar arrays and enough battery capacity to accommodate eclipse and RAVAN's various attitude orientations (see Table 1). Communications will use a redundant system including both a UHF radio and the Globalstar network (each can be used for command and telemetry communications).



**Figure 5: RAVAN 3U CubeSat. The RAVAN payload occupies the 1U section at the bottom of the figure, shown with its doors open. Four deployable solar arrays are right and left (the shadowed face of the space vehicle is shown; the solar panels are mounted on the opposite side). The UHF antenna extends from the front edge of the bus, and openings for the two star trackers are visible in the upper 1U section.**

Payload integration and testing will be performed at BCT in Boulder, Colorado, including complete RAVAN spacecraft vibration, thermal vacuum, and launch acceptance testing, such as day-in-the-life testing. RAVAN will be delivered to Cal Poly for launch vehicle integration in July 2016.

#### On-Orbit Operations

RAVAN is anticipated to launch in the second half of 2016 into an orbit that is nearly circular, sun-synchronous, and roughly 600 km. In fact, an orbit altitude of at least 550 km is required in order to view the entire Earth disk within the radiometer FOV ( $130^\circ$ ). The first month on orbit represents a commissioning

and check-out phase, during which time the radiometers will be protected from spacecraft outgassing. During this first month we will characterize the thermal environment of the payload and test the performance of the gallium black bodies, exercising them through multiple freeze–thaw cycles.

Following the check-out phase, RAVAN will begin five months (minimum) of operations comprising continuous nadir Earth observations with interspersed calibration maneuvers, as summarized in Table 1. The CubeSat will slew for the solar and deep space views, using the Sun to provide absolute calibration and on-orbit characterization of the radiometer angular responsivity. The operations phase of the flight will allow for the demonstration of using VACNTs for Earth radiometry, with the goal of achieving the accuracy, precision, and stability needed for climate measurements.

## CONCLUSIONS

The RAVAN CubeSat mission demonstrates an affordable, accurate radiometer that directly measures Earth-leaving fluxes of total and solar-reflected radiation. The key technologies integrated into the payload are a vertically aligned carbon nanotube radiometer absorber and a gallium fixed-point black body as a built-in calibration source. The flight model payload was delivered in June 2016 for integration with the spacecraft bus. With a planned launch in the second half of 2016, RAVAN will demonstrate that a compact spaceborne radiometer that is absolutely accurate to NIST-traceable standards can be built for low cost, thus enabling the development of an Earth radiation budget constellation that could provide global, diurnal measurements of outgoing radiation for superior predictions of future climate change.

## Acknowledgments

The work was supported by NASA’s Earth Science Technology Office through grant NNX13AM53G.

## References

1. Trenberth, K. E. and J. T. Fasullo, “Tracking Earth’s Energy,” *Science*, vol. 328, pp. 316–317, doi: 10.1126/science.1187272, 2010.
2. Hansen, J. et al., “Earth’s Energy Imbalance and Implications,” *Atmospheric Chemistry and Physics*, vol. 11, pp. 13,421–13,449, doi:10.5194/acp-11-13421-2011, 2011.
3. Trenberth, K. E., J. T. Fasullo, and J. Kiehl, “Earth’s Global Energy Budget,” *Bulletin of the American Meteorological Society*, vol. 90, pp. 311–323, doi: 10.1175/2008BAMS2634.1, 2009.
4. Gray, L. J. et al., “Solar Influence on Climate,” *Reviews of Geophysics*, vol. 48, doi:10.1029/2009RG000282, 2010.
5. Kopp, G. and J. L. Lean, “A New, Lower Value of Total Solar Irradiance: Evidence and climate significance,” *Geophysical Research Letters*, vol. 38, doi:10.5194/acp-11-13421-2011, 2011.
6. Trenberth, K. E. et al., “Climate Variability and Relationships between Top-of-Atmosphere Radiation and Temperatures on Earth,” *Journal of Geophysical Research–Atmospheres*, vol. 120, doi:10.1002/2014jd022887, 2015.
7. Harries, J. E. and C. Belotti, “On the Variability of the Global Net Radiative Energy Balance of the Nonequilibrium Earth,” *Journal of Climate*, vol. 23, pp. 1277–1290, doi:10.1175/2009jcli2797.1, 2010.
8. Loeb, N. G. et al., “Toward Optimal Closure of the Earth’s Top-of-Atmosphere Radiation Budget,” *Journal of Climate*, vol. 22, pp. 748–766, doi:10.1175/2008jcli2637.1, 2009.
9. Wiscombe, W. and C. Chiu, “The Next Step in Earth Radiation Budget Measurements,” *Molecular Nanostructures: XVII International Winterschool Euroconference on Electronic Properties of Novel Materials 1531*, pp. 648–651, doi:10.1063/1.4804853, 2013.
10. National Academies of Sciences, Engineering, and Medicine, “Achieving Science with CubeSats: Thinking Inside the Box,” *The National Academies Press*, Washington, DC, doi:10.17226/23503, 2016.
11. Mizuno, K. et al., “A Black Body Absorber from Vertically Aligned Single-Walled Carbon Nanotubes,” *Proceedings of the National Academy of Sciences*, vol. 106, pp. 6044–6047, doi:10.1073/pnas.0900155106, 2009.
12. Tomlin, N. A. et al., “Decrease in Reflectance of Vertically-Aligned Carbon Nanotubes after Oxygen Plasma Treatment,” *Carbon*, vol. 74, pp. 329–332, doi:10.1016/j.carbon.2014.03.040, 2014.
13. Rogers, A. Q. et al., “Small Satellite Initiatives: Building on Success,” presented at 30th Space Symposium, Technical Track, Colorado Springs, Colorado, May 21, 2014.