RAVAN CubeSat Results: Technologies and Science Demonstrated on Orbit

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ABSTRACT
The Radiometer Assessment using Vertically Aligned Nanotubes (RAVAN) CubeSat, launched November 11, 2016, is a pathfinder for a constellation to measure the Earth’s energy imbalance, which is the single most important quantity for predicting the course of climate change over the next century. RAVAN demonstrates small, accurate radiometers that measure top-of-the-atmosphere Earth-leaving fluxes of total and solar-reflected energy. The radiometers rely on two key technologies. The first is the use of vertically aligned carbon nanotubes (VACNTs) as radiometer absorbers. 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 gallium fixed-point black body calibration sources that serve as stable and repeatable references to track the long-term degradation of the sensors. Absolute calibration is maintained by regular solar and deep space views. The RAVAN payload flies on a 3U CubeSat that combines stellar attitude determination, sub-degree pointing, and UHF communication. We present the scientific motivation for the NASA-funded mission, key technologies tested in space, payload design, the 3U CubeSat bus, mission operations, instrument calibration, and the first results on-orbit.

SCIENCE MOTIVATION
Our ability to understand and predict Earth’s future climate is limited by our ability to track energy within the Earth system. Climate change is driven by changes in Earth’s global energy budget resulting from a very small yet important imbalance between the in-coming solar energy reaching the Earth system and the outgoing solar-reflected and thermally emitted energy. Current research suggests that EEI is on the order of +1 W/m² on an annual global mean basis in the current epoch (meaning that the outgoing energy is less than the incoming solar energy by about 0.3%), due to the net effect of anthropogenic emissions of greenhouse gases and aerosols. Accurately measuring EEI would improve the projection of future climate by climate models.

Two key goals lie at the frontier of climate observation from space: (1) global measurement of the Earth energy diurnal cycle at accuracies commensurate with the global imbalance and (2) measurement of EEI as a global synoptic constraint of the predictions of climate models. To achieve these challenging goals, a new approach to the Earth energy budget is needed. EEI 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 energy budget.

The maturation of small satellites, hosted payloads, and constellation technologies provides a unique and timely
opportunity for making the next great leap in Earth energy budget measurement. 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 30 or more. Such a constellation would enable accurate, un-tuned measurements of EEI 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 energy 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 energy from the ultraviolet (200 nm) to the far infrared (200 µm) with climate accuracy (better than 0.5 W/m² 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 energy budget constellation mission. RAVAN demonstrates two key technologies that enable accurate, absolute Earth energy measurements using a remarkably small instrument: radiometers with vertically aligned carbon nanotube (VACNT) absorbers and gallium black body phase-transition calibration sources.

Carbon nanotubes are an allotrope of carbon that, at a microscopic level, are essentially long, hollow graphene cylinders. 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. An example of a VACNT radiometer absorber is shown in Figure 1. 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. 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.

The second key technology is the gallium calibration source. Two gallium fixed-point black bodies serve as on-orbit infrared sources (shown in Figure 2) that, when coupled with deep space looks, provide an additional means to determine the offset for the total channels. We use the gallium solid-liquid phase transition (29.76°C) as a stable, repeatable reference for the black body emission to track the long-term degradation of the radiometer sensors.

Figure 1: Radiometer head assembly. The VACNT absorber is the 7-mm disk in the center.

Figure 2: Gallium black body cell (black disk), integral to radiometer door.

PAYLOAD

We treat measurement of the Earth’s outgoing energy as a simple irradiance measurement using thermal detectors with spectrally flat absorbers and precision apertures. The RAVAN payload comprises four independent radiometers in two pairs, as shown in Figure 3. 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 channel, measuring all energy 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 allow RAVAN to distinguish between solar-reflected sunlight and the Earth’s total emission. The radiometers have a wide field of view, 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.

The RAVAN payload has two re-closable doors, actuated by stepper motors, which cover the primary and secondary radiometer pairs. The doors protected the radiometers before launch and during commissioning, and they are 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.

The payload mass is less than 1 kg, draws 1.9 W of power (orbit average), and fits within a 1-U volume (<10x10x10 cm³). The RAVAN payload produces approximately 2.5 MB of science and housekeeping data per day.

CUBESAT AND ON-ORBIT OPERATIONS

The RAVAN radiometer payload is hosted on a 3U CubeSat bus designed and built by Blue Canyon Technologies, based on their XB3 design (Figure 4).

RAVAN launched on November 11, 2016, on an Atlas V rocket from Vandenberg Air Force Base in California into an orbit that is nearly circular, sun-synchronous, and close to 600 km. During the bus commissioning and check-out phase the radiometer doors remained closed, to reduce the risk of contamination. The mission then proceeded with payload commissioning, with “first light” in January 2017.

The principal calibration of RAVAN occurs on orbit, with the Sun as the primary, absolute standard and deep (cold) space characterizing the offset. The CubeSat slews for the solar and deep space views, using the Sun to provide both absolute calibration and on-orbit characterization of the radiometer angular responsivity. The integral gallium black body emitters monitor degradation of both the primary and secondary Total channels. RAVAN’s various configuration modes are summarized in Table 1.

Figure 3: 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).

Figure 4: RAVAN 3U CubeSat (1U payload at top in this photograph).

The 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. Communications are provided by a UHF downlink.
Table 1: Modes of operation

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

PRELIMINARY RESULTS

RAVAN made periodic Earth observations from mid-January 2017 through early March, following payload commissioning. The spacecraft’s SD card—our planned means of telemetry storage between UHF downlinks—failed in early March. Fortunately, it was possible to reprogram the payload to store its data in payload RAM. As of mid-April, we resumed operations, starting with a series of solar calibration sequences. Analysis of all the data collected to date is ongoing.

**Gallium Black Bodies**

The gallium black bodies have been undergoing phase transitions ever since launch, as the normal orbital temperature cycling of the spacecraft drives the melting and freezing of the cells each orbit, as shown in Figure 5. The gallium melt appears as the shoulder on the ascending side of the temperature oscillations. The freeze on the descending side is less clear in the figure, likely due to imperfect thermal equilibrium within the cell and coupling with the thermistor. The temperatures near the melt cells have been monitored since the payload was powered on mid-December 2016. Calibration of the radiometer Total channels is possible while actively controlling the cells at their melting points. Numerous black body calibrations have been performed.

**Radiometers**

The radiometer doors were opened for the first time on January 25, 2017, confirming that the door mechanisms work as designed. Further, this provided us with the first light on the sensors, as shown in Figure 6. Although the values shown have not been absolutely calibrated yet, the receiver signals have been scaled to reveal how well they track each other. There is excellent agreement between the individual Total channels and the individual shortwave channels. Further, there is qualitative agreement between the Total and SW channel pairs, as the Earth outgoing radiation varies with scene below the spacecraft as it flies in its orbit. Absolute calibration will be possible after recent solar calibrations have been analyzed.

![Figure 5: Temperature near gallium black body cell over eight consecutive orbits. Melting point of gallium (29.7646°C) indicated.](image)

![Figure 6: Radiometer “First Light.” Spikes near the terminator likely caused by glint.](image)

CONCLUSIONS

RAVAN is an ongoing CubeSat mission primarily to demonstrate technologies that could enable the development of an Earth energy budget constellation for global, diurnal measurements of Earth outgoing energy, which is of critical importance in predicting future climate change. Following its check-out phase,
RAVAN has performed periodic nadir Earth observations with interspersed calibration maneuvers. We have already collected enough data to meet most of our objectives. We have demonstrated using VACNTs for Earth radiometry and gallium black bodies for on-orbit calibration, with the goal of achieving the accuracy, precision, and stability needed for climate measurements. Continued observations will allow for a determination of the RAVAN sensors’ on-orbit stability.

Acknowledgments

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References