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VACNT versus Black Velvet: a coating analysis for the next-generation Earth Radiation Budget radiometer

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ABSTRACT

Climate on Earth is determined by the Earth Radiation Budget (ERB), which quantifies the incoming and outgoing radiative energy fluxes at the top-of-atmosphere (TOA). The ERB can be monitored from space by non-scanning wide field-of-view radiometers (WFOV), or by scanning narrow field-of-view radiometers. Recently, WFOV radiometers have gained renewed interest as illustrated by the development of the RAVAN and SIMBA 3U CubeSats. RAVAN uses a Vertically Aligned Carbon Nanotubes (VACNT) coating, while the SIMBA CubeSat uses a novel cavity-based geometry with a Black Velvet coating. Both VACNT and Black Velvet are diffuse coatings, but when applied to flat sensors, the VACNT coating has a significantly lower reflectivity in comparison to classic diffuse or specular black coating materials. When used on a cavity radiometer, it is currently unclear if a VACNT coating would improve the measurement accuracy compared to other diffuse coatings, such as Black Velvet.

In this paper, we therefore investigate the potential benefits of using the VACNT coating as an alternative for Black Velvet, in our in-house developed radiometer. Our analysis includes the evaluation of the influence of the cavity geometry as well as the coating absorption factor. The comparison of the VACNT with the Black Velvet coating is based on the absorption factor of the cavity that is determined using radiation view factor calculations. Scattering and stray-light analyses are carried out using commercially available ray-tracing software (ASAP\textsuperscript{®}, Breault Research). We evaluated whether the coating or the geometry is the main contributing factor to the performance of the radiometer. As a conclusion, we observed that for cavity-type radiometers, the difference in the cavity absorption factor between Black Velvet and VACNT becomes negligible, favoring the use of Black Velvet, since Black Velvet has a long space heritage and appears more user friendly from a fabrication point of view, as it can be deposited in an easier and more reproducible manner on the radiometer cavity walls, including non flat surfaces.

Keywords: Earth Radiation Budget; Earth Energy Imbalance; Space instrumentation; Radiometer; Optical modelling; Coating; Black Velvet; VACNT

1. INTRODUCTION

The radiative energy fluxes at the top-of-atmosphere (TOA) are described by the so-called Earth Radiation Budget (ERB),\textsuperscript{1} which plays a major role in the climate system. The primary source of energy in the ERB is solar radiation, of which 30\% is reflected by the Earth. The remaining energy is absorbed by the Earth and is re-emitted to space under the form of thermal radiation. Global warming is caused by an unbalanced ERB, due to an increasing amount of greenhouse gases in the atmosphere, which is itself caused by anthropogenic activity. This small but non-zero net energy is called the Earth Energy Imbalance (EEI), and it is one of the most crucial parameters to be monitored in our pursuit to understand climate change.\textsuperscript{2–4}

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Wide field-of-view (WFOV) radiometers, observing the Earth from limb to limb,\textsuperscript{5} were used in the earliest measurements of the ERB. This measurement principle has been adapted during the Earth Radiation Budget Experiment (ERBE),\textsuperscript{6} where the low resolution ERB measurements obtained using WFOV radiometers were compared with the higher resolution measurements from the scanning radiometers. In addition, these scanning radiometers avoided the thermal offset problems of WFOV radiometers.\textsuperscript{7} Hence the CERES program continued with scanning radiometers. But recently, WFOV radiometers have gained renewed interest as illustrated with the development of the SIMBA\textsuperscript{9} and RAVAN\textsuperscript{10} 3U CubeSats. Both CubeSats have a similar working principle, but use different strategies to achieve an improved measurement of the radiative flux in comparison to the previous WFOV radiometers. The SIMBA CubeSat uses a novel cavity-based geometry with a Black Velvet coating. On the other hand, the RAVAN CubeSat uses the Vertically Aligned Carbon Nanotubes (VACNT) coating on flat sensors. When applied to flat sensors, the VACNT coating has a significantly lower reflectivity in comparison to classic diffuse or specular black coating materials.\textsuperscript{10} For this reason, the VACNT coating is also expected to be used for future space missions that target the measurement of the ERB, such as the Libera mission\textsuperscript{11} recently selected by NASA, and the BABAR-ERI\textsuperscript{12} from LASP laboratory. When used on a cavity radiometer, it is not clear yet if the VACNT coating would improve the measurement accuracy compared to other diffuse coatings, such as Black Velvet.

We propose a new concept to measure the radiative fluxes at the TOA, using a combination of space-based instruments. The first instrument is a WFOV radiometer, which aims to measure accurately the total Earth’s outgoing energy. Its estimated accuracy equals 0.44 W/m\textsuperscript{2}, which is a 10-fold improvement over the NASA CERES instruments.\textsuperscript{13} This radiometer is supplemented with high-resolution shortwave (SW, [400–1100] nm),\textsuperscript{14} and longwave (LW, [8–14] \(\mu\)m) WFOV cameras, providing a better radiometer accuracy, increasing the spatial resolution, and enabling the spectral separation between Reflected Solar Radiation (RSR) and Outgoing Longwave Radiation (OLR).

This paper focuses on the design and simulated performance of the coating in our in-house developed WFOV radiometer. In particular, we investigate the potential benefits of using the VACNT coating as an alternative for Black Velvet. We give the radiometer model (section 2) and we analyze its performance to characterize the cavity absorption factor (section 3). Section 4 closes this paper with a summary and a discussion on the implications for future ERB radiometers.

2. METHODS

We first describe our radiometer model, necessary to perform the optical analysis (section 2.1). First of all, we define the cavity geometry, the optical sources, as well as the properties of the two coating materials that are used in these simulations: Black Velvet and VACNT. Secondly, we explain the radiometer analysis procedure (section 2.2). To evaluate the cavity absorption factor of our radiometer, we calculate the view factors, which only requires the knowledge of the cavity geometry. A more specific optical analysis is then performed in ASAP®, Breault Research: the flux leaving the cavity is computed, the cavity absorption factor is derived. To complete our analysis, we investigate the irradiance uniformity at the hemispherical part of the cavity. Finally, we discuss the methods to optimize the cavity geometry, with the outgoing flux as our merit function (section 2.3).

2.1 Radiometer model

2.1.1 Cavity geometry

Radiometers used for Total Solar Irradiance monitoring can be made in different geometries, as a cone shape (ACRIM,\textsuperscript{15} TIM\textsuperscript{16}), cylinder (DIARAD\textsuperscript{17}), or inverted cone (PMO\textsuperscript{18}). To monitor the Earth’s radiation, a wide field-of-view, typically of 127\degree from an altitude of about 700 km, is required to observe the Earth from limb-to-limb. Therefore, to reach this wide FOV, a novel cavity shape is needed. We propose to use a wide field-of-view radiometer as described in.\textsuperscript{13} More specifically, the cavity is composed of a near-hemispherical part and a conical part. Such a cone, with an appropriate baffle, allows the radiation to come from a field-of-view exceeding 135\degree, which is exceeding the required 127\degree and allows for pointing errors.

In our model, the diameter of the cavity aperture equals 6 mm. Below the cavity radiometer, there is a baffle with a precision aperture of 5 mm. The cavity radiometer aperture is slightly larger than the precision aperture
to ensure that no radiation is stopped by the cavity aperture. The outlook of the radiometer with the baffle is illustrated in Figure 1.

![3D views of the cavity with the baffle](image)

Figure 1. 3D views of the cavity with the baffle: side view (left) and bottom view (right).

### 2.1.2 Sources

Two pointing modes, therefore two cases, are considered for the radiometer: Solar radiation and Earth’s radiation (Figure 2). Solar radiation is only used for calibration purposes. This source can be modeled as a 5 mm diameter beam (since it passes through the precision aperture first) entering the aperture of the cavity, with a very small field-of-view of 3°. For Earth’s radiation, we consider the Earth’s emitted radiation properties as Lambertian. Considering that the radiation passing through the baffle comes from an angle of 127°, we can model this radiation as a Lambertian emitter with $2\theta = 127°$, which is placed at the radiometer cavity entrance. The emitting disk has a diameter of 5 mm, since as the solar radiation, the Earth’s radiation passes through the precision aperture first.

![Image of Earth and Sun](image)

**Total Solar Irradiance:** 1362 W/m²
**Incoming:** 340.4 ± 0.2 W/m²

**Total Earth’s Outgoing Irradiance**
- Reflected (SW): 101.5 ± 2.7 W/m²
- Emitted (LW): 238.0 ± 2.0 W/m²

**Earth Energy Imbalance**

$$EEI = \text{Incoming} - \text{Reflected (SW)} - \text{Emitted (LW)}$$
$$= 0.9 ± 0.3 \text{ W/m}²$$

Figure 2. Earth viewed by the WFOV radiometer. Occasional solar pointing will allow intercalibrating the Incoming Solar Radiation and the Earth’s Total Outgoing Radiation measurements. SW stands for shortwave and LW for longwave.
2.1.3 Coating and absorption factor
The interior cavity walls of the radiometer are coated with a black paint that allows to absorb incoming radiation. Two coating materials are considered: Black Velvet\textsuperscript{20} and VACNT.\textsuperscript{10} For the LW spectral region (8–14 μm), absorption factors of Black Velvet and VACNT equal 0.97 +/- 0.01 and 0.998 +/- 0.001 respectively. While for the SW spectral region (400–1000 nm), absorption factors of Black Velvet and VACNT equal 0.97 +/- 0.01 and 0.999 +/- 0.001 respectively.

For perpendicular illumination, the absorption factors for LW and SW are equal within the uncertainty. Also, we consider three illumination cases: (1) LW Earth, for which a Lambertian source of 127° is simulated ; (2) SW Earth, having the same angle but at different wavelengths ; (3) solar, a SW source with an angle of incidence of ±1.5°. Because we define the source with a total emitting angle of 127° and the conical part of the cavity with a bigger acceptance angle of 135°, all generated rays will first encounter the hemispherical part of the cavity. For this analysis performed in ASAP®, Breault Research, we use the commands SPLIT 2 for specular reflection and LEVEL 2 for scattered light, a total flux of 100 (in arbitrary units), and 50000 rays.

2.2 Radiometer analysis
2.2.1 View factors calculation: absorption factor
We define the absorption factor of the cavity as the part of the radiation entering the precision aperture that is absorbed within the cavity and subsequently measured with an electrical substitution detector. The radiation that is not measured is 1) the reflected radiation that escapes through the precision aperture, and 2) the reflected radiation that is absorbed by the backside of the precision aperture. The cavity absorption factor depends on the angular distribution of the measured radiation and of the coating material on the inside of the cavity.

The cavity absorption factor for each of the illumination cases, when considering the different coating absorption factors, can be calculated using the view factors from\textsuperscript{21} and\textsuperscript{22}

2.2.2 Outgoing flux
We are interested in the flux that leaves the cavity, what we will be calling the outgoing flux. Since in this model, the source is placed at the entry of the cavity, a way to determine the flux leaving the cavity is to put a virtual detector just below the cavity. This detector is composed of two parts:

• the main part is a circular plane ;
• the second part allows to capture the grazing rays (i.e. the rays with a high angle with respect to the Z-axis).

2.2.3 Irradiance
In addition to the absorption factor, it is also interesting to assess the lighting uniformity. While an analysis on the thermal non-uniformity has already been performed in a previous publication,\textsuperscript{13} we investigate the irradiance uniformity on the hemispherical part of the cavity. In general, the irradiance uniformity is quantified by the minimum over maximum irradiance ratio of the light distribution. However, owing to the screen engulfing the outside of the cavity, our minimum irradiance will be zero. Therefore, we define our irradiance uniformity \((I_{\text{uniformity}})\) by the ratio of the average \((I_{\text{average}})\) and maximum \((I_{\text{max}})\) irradiance of the light distribution instead (equation 1).

\[
I_{\text{uniformity}} = \frac{I_{\text{average}}}{I_{\text{max}}}
\]  

2.3 Geometry optimization
We started our simulations with a cavity geometry composed of a perfect hemispherical part and a conical part. However, it could be beneficial to use a near-hemispherical part, instead of a perfect one. Therefore, after the comparison analysis and selection of the coatings, an optimization of the coated cavity shape will be performed by optimization of its semi-length along the Z-axis. The size of the hemispherical part of the cavity will thus be optimized. Since we want to minimize the light leaving the cavity, we pursue to minimize the flux reaching the detector, which is our merit function.
3. RESULTS

We first illustrate the radiometer model (section 3.1), which is based on the methods given in section 2.1. The simplified geometry corresponds to the one when both parts of the cavity (the hemispherical part and the conical part) are in contact with each other. As an alternative to this model, a gap of 2 mm is introduced between these two parts to avoid thermal conduction, which is an important feature of the cavity, as described in a previous publication. Then, we analyze the cavity radiometer absorption factor (section 3.2) using view factors calculation, as well as a coating analysis performed with the optical software ASAP®, Breault Research. Both simplified geometry and geometry with the gap are analyzed. The latter also benefits of an analysis of the irradiance uniformity. Finally, in section 3.3, we optimize the cavity geometry with a gap and with the Black Velvet coating for the Earth-observing mode, which is the case where the outgoing flux is maximum.

3.1 Radiometer model

3.1.1 Simplified geometry

The radiometer model described in section 2.1 is illustrated with plotted rays in Figure 3. This model enables us to quantify the outgoing flux.

Figure 3. The cavity radiometer is composed of a hemispherical part, a conical part, and has an aperture where the radiation is entering. In our ASAP model, the detector (in yellow) is an absorptive structure that intercepts the outgoing light. Rays are plotted in black.

3.1.2 Model with a gap

An alternative to this model, we included a gap of 2 mm between the hemispherical part and the conical part of the cavity, as illustrated in Figure 4. The gap is used to avoid thermal conductivity between both parts. It is modelled as an absorptive part that stops the propagation of light.
3.2 Radiometer analysis

3.2.1 Absorption factor from view factors calculation

A first estimation of the absorption factor of the cavity can be made according to view factors calculation, as discussed in section 2.2.1. In order to simplify the calculations, we use the view factors calculation only on the simplified radiometer geometry, without the gap between the hemispherical part and conical part of the cavity. The cavity absorption factor, for each of the 3 illumination conditions discussed in section 2.1.3, is presented in Table 1, for both Black Velvet and VACNT coatings.

Table 1. Calculated cavity absorption factor, using view factors, when applying a Black Velvet and VACNT coating, when measuring Earth’s LW radiation, Earth’s SW radiation, and solar calibration.

<table>
<thead>
<tr>
<th></th>
<th>Black Velvet</th>
<th>VACNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW Earth</td>
<td>0.99985 +/- 0.00005</td>
<td>0.999990 +/- 0.000010</td>
</tr>
<tr>
<td>SW Earth</td>
<td>0.99985 +/- 0.00005</td>
<td>0.999995 +/- 0.000005</td>
</tr>
<tr>
<td>Solar</td>
<td>0.99980 +/- 0.00007</td>
<td>0.99980 +/- 0.00007</td>
</tr>
</tbody>
</table>

The VACNT coating shows a higher absorption factor than Black Velvet. However, the impact on the final accuracy of the radiometer is negligible. Considering the drawbacks associated with VACNT (cost, deposition technique on non-flat surfaces), Black Velvet could be preferred.

3.2.2 Coating analysis with ASAP®, Breault Research: model without gap

In a next step, the coating analysis was performed using non-sequential ray tracing software (ASAP®, Breault Research). First, the same simplified radiometer geometry as in the previous section was considered, thus without the gap.

Following the methods described in section 2.1.3, and doing a path analysis, we infer the values of the outgoing flux, the portion of flux that is escaping the cavity radiometer. This outgoing flux is quantified by the virtual
detector below the cavity radiometer. The simulated results are summarized in Table 2 that compares the coating materials Black Velvet and VACNT for the three illumination cases: LW Earth, SW Earth and solar. It can be seen from this Table that more flux is escaping when observing the Earth than the Sun. Also, in all cases, the escaping flux is less than 0.0009% of the incoming flux.

Table 2. Computed outgoing flux (in % of the incoming flux) for the radiometer model without the gap, when applying a Black Velvet and VACNT coating, when measuring Earth’s LW radiation, Earth’s SW radiation, and solar calibration.

<table>
<thead>
<tr>
<th></th>
<th>Black Velvet</th>
<th>VACNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW Earth</td>
<td>0.000794%</td>
<td>0.000005%</td>
</tr>
<tr>
<td>SW Earth</td>
<td>0.000794%</td>
<td>rounded to 0.000000%</td>
</tr>
<tr>
<td>Solar</td>
<td>0.000859%</td>
<td>0.000305%</td>
</tr>
</tbody>
</table>

Considering numerical errors, this analysis is not in contradiction with our previous analytical calculation using view factors. Therefore, we are confident in this radiometer model. In the next section, the radiometer model will be sophisticated to assess the loss of light due to the gap between the hemispherical part and the conical part of the cavity.

3.2.3 Coating analysis with ASAP®, Breault Research: model with a gap

The previous analysis performed in ASAP®, Breault Research, was performed similarly to the preliminary analysis using view factors. A simplification was made on the geometry, since the gap between the hemispherical and the conical parts was absent. In this section, we present the results for a deeper analysis, considering the gap between the hemispherical part and the conical part of the cavity. The simulated results are given in Table 3. The present analysis shows that in all cases, the escaping flux is less than 0.253% of the incoming flux.

Table 3. Computed outgoing flux (in % of the incoming flux) for the radiometer model with the gap, when applying a Black Velvet and VACNT coating, when measuring Earth’s LW radiation, Earth’s SW radiation, and solar calibration.

<table>
<thead>
<tr>
<th></th>
<th>Black Velvet</th>
<th>VACNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW Earth</td>
<td>0.2528%</td>
<td>0.0170%</td>
</tr>
<tr>
<td>SW Earth</td>
<td>0.2528%</td>
<td>0.0086%</td>
</tr>
<tr>
<td>Solar</td>
<td>0.2195%</td>
<td>0.0072%</td>
</tr>
</tbody>
</table>

Considering a total Earth’s outgoing radiative flux equals 340 W/m² (Figure 2), Table 4 gives the absolute loss of flux when observing the Earth from space. In all cases, the loss of light is less than 1 W/m².

Table 4. Escaping flux when observing Earth from space, considering a total Earth’s outgoing radiative flux of 340 W/m².

<table>
<thead>
<tr>
<th></th>
<th>Black Velvet</th>
<th>VACNT</th>
</tr>
</thead>
<tbody>
<tr>
<td>LW Earth</td>
<td>0.86 W/m²</td>
<td>0.058 W/m²</td>
</tr>
<tr>
<td>SW Earth</td>
<td>0.86 W/m²</td>
<td>0.029 W/m²</td>
</tr>
<tr>
<td>Solar</td>
<td>0.2746 W/m²</td>
<td>0.024 W/m²</td>
</tr>
</tbody>
</table>

Using a cavity geometry, the coating absorption factor is of less importance than when considering a pure flat sensor. In fact, a flat sensor coated with Black Velvet would absorb 97% of the incoming flux, resulting in a loss of 10.2 W/m² when observing the Earth, while a sensor coated with VACNT would only lose 0.34 W/m² (in the SW range, which is the best case scenario).
VACNT can be considered as a superior coating, while the weaker absorption of Black Velvet can be greatly reduced by the cavity geometry. Furthermore, some drawbacks are associated with VACNT, as its high cost and more complex deposition technique (see Vertically Aligned Carbon Nanotube Growth Procedure). Therefore, we advice to use Black Velvet, as a flux loss of 1 W/m² is acceptable, but keep VACNT in mind in case one should achieve a flux loss of only 0.03 W/m² in the SW and only 0.06 W/m² in the LW.

3.2.4 Irradiance uniformity

Irradiance uniformity is assessed with a map of irradiance on the hemispherical part of the cavity (Figure 5). Using equation 1, we obtain:

\[ I_{\text{uniformity}} = \frac{I_{\text{average}}}{I_{\text{max}}} = \frac{0.043}{0.086} = 0.502 \]

Figure 5. Irradiance at the hemispherical part of the cavity. Minimum irradiance equals 0, at the outside of the cavity. Maximum irradiance equals 0.086. Average irradiance equals 0.043.

3.3 Geometry optimization

In this section, we present the results for the cavity geometry optimization discussed in section 2.3. As previously stated, we target to minimize the outgoing flux, which is our merit function, and we do so in the case of Earth observation with the Black Velvet coating. Our variable being the cavity geometry, we analyze the effect of changing the distance \( z \) between the top of the hemispherical part of the cavity, and the precision aperture. The hemispherical part is first modelled as a hemi-ellipse with \((x, y, z) = (24, 24, 24)\) mm. Different optimizations were made, by gradually refining our search for the optimal value, to end up with a value \( z_{\text{optimized}} = 25.455 \). For that value, the merit function equals 0.00514. Figure 6 illustrates the optimized radiometer model and the associated irradiance map at the hemispherical part of the cavity. For this optimized value, 0.2499% of the incoming flux is escaping the cavity, resulting in a flux loss of 0.849 W/m² when observing the Earth from space. This optimization shows that the geometry was already quiet good from the start.

4. SUMMARY AND CONCLUSION

Climate on Earth is determined by the Earth Radiation Budget (ERB), which quantifies the incoming and outgoing radiative energy fluxes at the top-of-atmosphere (TOA). The ERB can be monitored from space by non-scanning wide field-of-view radiometers (WFOV), or by scanning narrow field-of-view radiometers. Recently, WFOV radiometers have gained renewed interest as illustrated with the development of the SIMBA and RAVAN 3U CubeSats. Both CubeSats have a similar working principle, but use different strategies to achieve an improved measurement of the radiative flux in comparison to the previous WFOV radiometers. The SIMBA CubeSat uses a novel cavity-based geometry with a Black Velvet coating. On the other hand, the RAVAN CubeSat uses the Vertically Aligned Carbon Nanotubes (VACNT) coating on flat sensors.
When applied to flat sensors, the VACNT coating has a significantly lower reflectivity in comparison to classic diffuse or specular black coating materials. For this reason, the VACNT coating is also expected to be used for future space missions that target the measurement of the ERB, such as the Libera mission recently selected by NASA, and the BABAR-ERI from LASP laboratory. When used on a cavity radiometer, it is currently unclear if a VACNT coating would improve the measurement accuracy compared to other diffuse coatings, such as Black Velvet.

In this paper, we have investigated the potential benefits of using the VACNT coating as an alternative for Black Velvet, in our in-house developed radiometer. Our radiometer is composed of a hemispherical part and a conical part, and supplemented by a baffle and a precision aperture featuring a field-of-view of 135°. It allows monitoring the Earth’s radiative fluxes from limb-to-limb from an altitude of about 700 km.

Our analysis includes not only an evaluation of the influence of the cavity geometry, but also of the absorption factor of the coating. We compared VACNT with Black Velvet by considering the absorption factor of the cavity, using radiation view factor calculations, as well as scattering and stray-light analysis carried out with commercially available ray-tracing software (ASAP®, Breault Research). In a first instance, the geometry was simplified, not taking into account the loss of light due to the gap between the hemispherical part and the conical part of the cavity. Subsequently, the gap has been modeled as an absorptive part, taking into account the loss of light escaping through this gap. After an optimization of the cavity shape using the outgoing cavity flux as a merit function, we have visualized the irradiance on the hemispherical part of the cavity, and we assessed the flux that is leaving the cavity.

Finally, we made a performance comparison between cavity and a flat sensor coated with VACNT. We have demonstrated that for cavity-type radiometers, the difference in the cavity absorption factor between Black Velvet and VACNT becomes negligible when observing the Earth from space, and for a requirement of 1 W/m² of accuracy. If the loss of light due to the gap can be mitigated, the difference in these two coating materials becomes even more negligible, even for more stringent requirements on the accuracy.

Black Velvet has a long space heritage and appears to be more user friendly regarding the fabrication, as it can be deposited in an easier and more reproducible manner on our radiometer cavity walls, including non flat surfaces. Consequently, this research provides valuable insights into the influence of the coating parameters on the radiometer design, paving the way towards an improved next-generation ERB radiometer.

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