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The Distributed Electronic Cosmic-ray Observatory (DECO)

Justin Vandenbroucke,[a,*] Alicia Mand,[a] Runze Li[a] and Alex Pizzuto[a]

[a] *Wisconsin IceCube Particle Astrophysics and Department of Physics, University of Wisconsin–Madison, Madison, WI, USA*

E-mail: justin.vandenbroucke@wisc.edu, aemand@wisc.edu

The Distributed Electronic Cosmic-ray Observatory (DECO) is a project that enables users to detect cosmic rays and other ionizing radiation with their own cell phones. The DECO app treats cellphone cameras as silicon track detectors. Event images are uploaded to a web-based database where users and other members of the public can query, download, and analyze them. A convolutional neural network automatically classifies events by morphology for particle identification. DECO detects atmospheric muons through their ionization loss in camera image sensors. It also detects radioactive decay products, including electrons that undergo multiple Coulomb scattering and gamma rays that Compton scatter. Our GEANT-based detector Monte Carlo simulation produces images qualitatively and quantitatively similar to those of DECO experimental data. The simulation is well suited for training image classifiers based on machine learning and quantifying the performance of image classifiers and event reconstruction algorithms. DECO makes otherwise invisible particles and phenomena visible to members of the public using their own devices, applying the same concepts and technologies as professional particle physics detectors. We present an overview of the DECO project, which lies at the nexus of education, outreach, and research.

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1. Introduction

Here is where the intro will go

1.1 DECO overview

DECO continuously records images from the camera image sensor of a cell phone or other device. A low-resolution version of the image is analyzed to determine multiplicity of pixel brightness and those that pass this cut are selected as particle event candidates and processed further at a higher resolution. Candidates that meet a minimum threshold of bright pixels are classified as "events" and synchronized to the central server at the Wisconsin IceCube Particle Astrophysics Center in Madison, WI. The DECO server classifies the morphology of each event using a deep-learning based convolutional neural network (CNN). Users can browse events from their device or any other user's devices through the DECO database via a webpage on the main DECO website [1]. A screenshot displaying the DECO application can be seen in Figure 1.

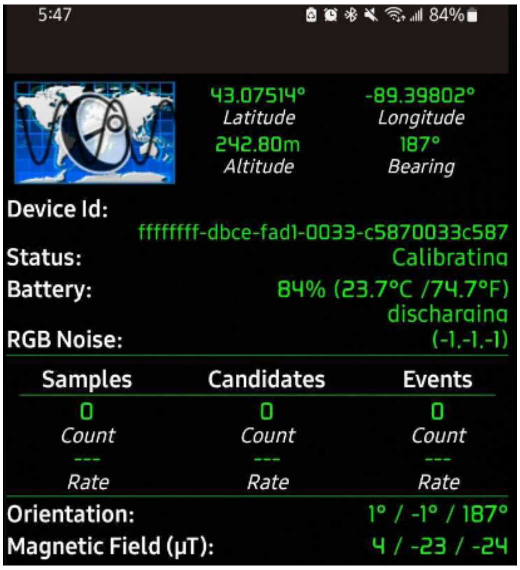

Figure 1: Screen shot of the DECO app running on an Android device.

1.2 Morphological event classification

DECO is capable of detecting and classifying three different event morphologies: tracks, worms, and spots. Tracks are long paths traced out by muons from a high-energy (~GeV) cosmic-ray. This results in a straight line of bright pixels in the final data product. Worms, or "wandering tracks" are the result of electrons which have undergone multiple Coulomb scattering interactions, giving the defining worm-like shape of this morphology. Spots are small near-circular clusters of pixels. They could be produced by a variety of particle interactions including (1) muons incident normal to the sensor (2) alpha particles, which have a very short range in silicon, or (3) gamma rays that Compton scatter to produce a low-energy electron that is absorbed in the silicon within a short distance [2].

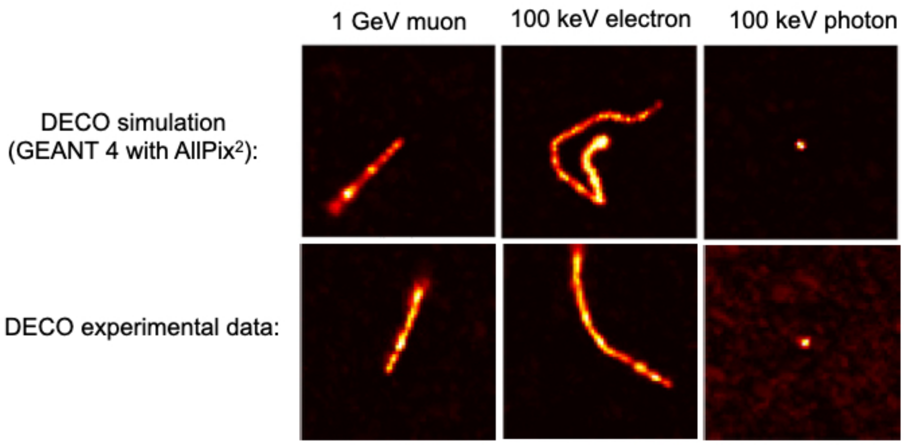

Figure 2: Comparison of simulated and experimental DECO images. The label above each simulated image provides the true particle identity and energy of the incident particle. The identity and energy of the incident particle in the experimental images are unknown. The good similarity between the images indicates that the bottom row of experimental images could be produced by (from left to right) an atmospheric muon, a beta particle produced by radioactive decay that undergoes multiple Coulomb scattering inside the sensor, and a gamma ray from radioactive decay that undergoes Compton scattering inside the sensor.

1.3 GEANT4 simulation and data / Monte Carlo comparisons

We have developed an end-to-end simulation of DECO, which is described in detail in [3]. We simulate particle interactions using GEANT4 [4], a toolkit for simulation of particle interactions in matter, and Allpix^2 [5], an open-source framework for the simulation of silicon-based pixel detectors. Using these simulation packages, we simulated a silicon detector similar to the CMOS camera image sensor in an HTC Wildfire cell phone. We simulated muons, electrons, and photons within an energy range of 10 keV to 100 GeV. After the particle interaction and silicon sensor simulation, we apply a Bayer filter and white balancing to the simulated data, approximating the processing that occurs in experimental images recorded by DECO. We then add real noise images obtained from experimental data recorded in dark conditions. The result of the simulation is a set of images in the same data format as experimental DECO images, for which the injected true Monte Carlo event properties (incluindg particle identity, energy, direction, and position) are known. This simulation framework produces images that agree qualitatively with experimental data recorded by DECO, as illustrated in Figure 2. Furthermore, we analyze both simulated and experimental data quantitatively and show that various image metrics agree well between experimental data and Monte Carlo. [3].

Figure 3 summarizes the results from GEANT4 simulation of individual DECO events, for the example case of incident muons. The muons are simulated spanning seven orders of magnitude in kinetic energy. Each incident particle begins at the CMOS sensor surface. For each simulated incident particle, the total energy deposited in the CMOS sensor is calculated from the simulation. This corresponds to the visible or detected energy, which for some combinations of incident particle identity and true energy can be used to infer the true energy of the incident particle. For each incident particle kinetic energy, the distribution of deposited energy is shown as a blue histogram. The mean

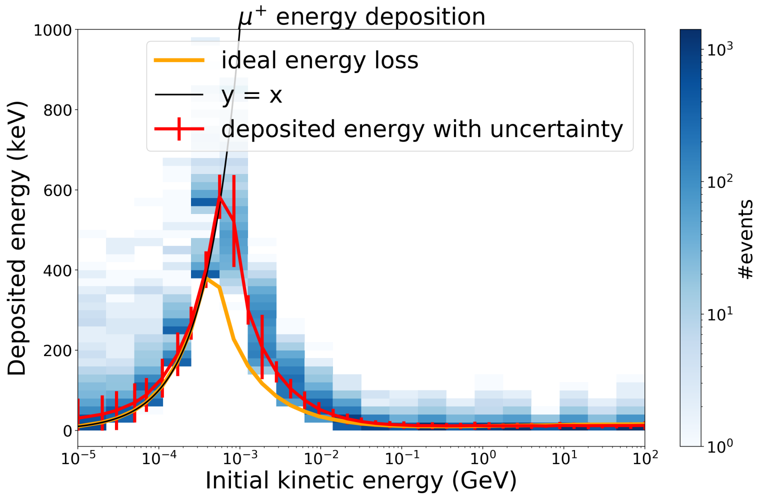

Figure 3: Distribution of energy deposited in the sensor as a function of incident particle kinetic energy, according to GEANT4 simulations of muon propagation through a DECO sensor. The distribution of simulate event deposited energies is shown in the blue histogram.

and standard deviation are plotted in red. For the example of incident muons, shown in the figure, there are several regimes of interesting physics are evident.

At the lowest energy range, the particle energy is insufficient to penetrate through the sensor, so the sensor absorbs the full particle energy and acts as a calorimeter, with the deposited energy nearly equal to the incident particle kinetic energy, as indicated by comparison to the yellow $y = x$ line. Some of these low-energy muons decay within the sensor, resulting in an electron ("Michel electron") with high kinetic energy. This results in a tail of the histogram at high deposited energy, and offsets the mean behavior to slightly greater deposited energy than the incident muon kinetic energy. The lowest energy muons are most likely to decay before exiting the sensor, resulting in the largest offset.

At the higest energy range, the muon is a through-going minimum ionizing particle, resulting in a constant deposited energy, which is independent of the incident particle energy and is a small fraction of it. Given the sensor thickness, the deposited energy can be calculated analytically in the low-energy, high-energy, and intermediate-energy regimes using the Bethe-Bloch equation, the result of which is indicated by the yellow "ideal energy loss" curve. This analytical calculation neglects scattering of the particle within the sensor. At high energy this provides an accurate estimate because the scattering is negligible, and at low energy it is accurate because the total kinetic energy is typically deposited within the sensor regardless of whether it scatters or not. In the intermediate regime, however, scattering of the incident particle within the sensor increases its total path length and therefore its total deposited energy in the sensor, with respect to the straight-line analytical calculation. This explains the offset of the red curve above the yellow curve in the figure.

The same principles of relating deposited energy to true incident particle energy, which are well understood and quantified by GEANT4 in this application to DECO, apply to professional particle and astro-particle detectors and can be used to teach these concepts to students and the

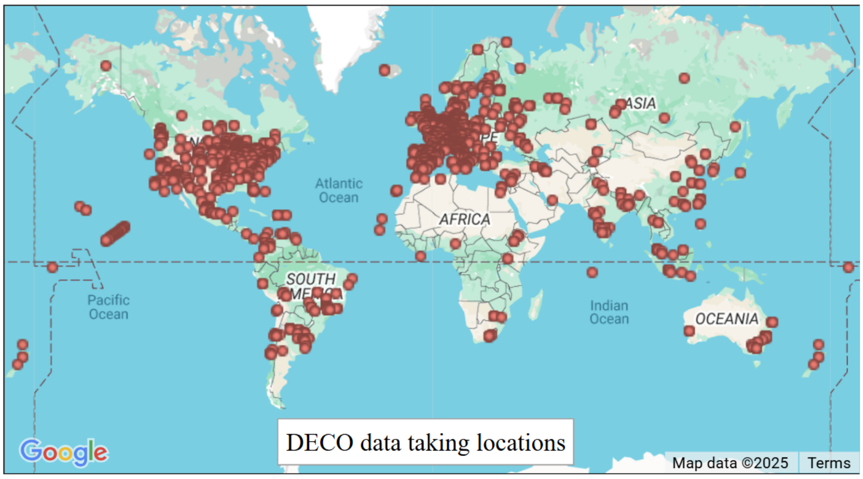

Figure 4: Map of DECO data collection locations. DECO users have recorded data in over 80 countries and all 7 continents including Antarctica.

public.

2. Education and Outreach

Aside from the research goal of detecting cosmic ray muons, DECO serves as an excellent tool for introducing the general public and students to cosmic ray research. Since being made public in Fall of 2014, DECO has been used across all 7 continents in over 60 countries. A map depicting all of DECO's data-taking locations is visible in Figure 4. Additionally, all DECO data is made available via a web-based interface on the main DECO website. Users can select individual events, including their own within 24 hours of data taking. Individual events are displayed as a cropped image with its respective coordinates. For security, the latitude and longitude are degraded to 0.01° resolution. DECO allows students and citizen scientists to develop a research interest through hands-on and inquiry-based learning, develop a collaborative mindset and approach, and incorporate critical thinking and problem solving with technology.

3. Future Prospects

In the future, we hope to improve the zenith reconstruction of events by taking advantage of track length and depletion depth in the silicon detector. Fortunately, previous studies [3] set the groundwork by measuring the depletion depth of the HTC Wildfire model of cellphones. The depletion depth, in conjunction with measurements of track length using using the aid of computer vision, will be used to determine the incoming angle of cosmic ray muons. In principle, this work could be extended to other models of cellphones with similar measurements of both depletion depth and track length. Additionally, DECO for iOS devices is currently in development.

figures, from white board planning:

(1) world map (2) data/MC image gallery (3) confusion matrix (4) data/mc quantitative comparison

cite: previous ICRC proceedings, journal papers (evidence of atm mu, CNN classifier for PID, GEANT 4 sims and data/mc comparison)

conclusion and outlook: include prospects for improved reco; redevelop ML classifier based on MC truth; iOS

4. Conclusion

DECO is a citizen science project that enables users to record and analyze cosmic ray muons and other energetic subatomic particles using a cell phone app and interactive web site. DECO is designed for education and outreach for students and the general public. We have demonstrated that DECO detects atmospheric (cosmic-ray) muons, classified event morphology (and likely particle identity) using a deep-learning convolutional neural network, and developed an end-to-end simulation that produces simulated DECO images with good fidelity to experimental images and in the same format, within known incident particle identity and energy. We have demonstrated long-term plans for angular reconstruction improvement and the use of simulation for CNN training.

5. Acknowledgments

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