Meiga-n: A Simulation Chain for Cosmic-Ray Neutron Sensing

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This work studies the interaction of cosmic rays, high-energy particles of astrophysical origin with energies ranging from 10^9 eV to 10^{20} eV, which produce secondary particles, including neutrons, when they collide with atmospheric nuclei. These neutrons can be used to non-invasively estimate soil moisture through cosmic-ray neutron sensors (CRNS), opening the possibility of using this technology in precision agriculture to optimize the use of water and other agricultural resources. This work presents and validates MEIGA-n, a modular simulation chain developed to calibrate these sensors and enable their application in regions lacking dedicated monitoring networks. The framework combines CORSIKA for extensive air shower development with Geant4 for particle transport in the lower atmosphere and soil, incorporating continuous boundary conditions to ensure flux conservation. Its modularity allows the particle flux to be stored and reused at each stage, atmospheric cascade, lower-atmosphere transport, or soil interaction, without repeating prior simulations, and adapted to any geographic location through its altitude, latitude, and atmospheric configuration. Validation against pure CORSIKA simulations for Bucaramanga (956 m a.s.l.) yielded discrepancies below 6% in the range of 17 MeV to 10^5 MeV neutron flux. The epithermal neutron flux follows the expected inverse relation with soil moisture, although systematically 7-16% below the standard reference curve reported in the literature, an effect attributed to site-specific soil mineralogy. Capture gamma-ray spectroscopy enables qualitative identification of nitrogen, phosphorus, and potassium through their characteristic emission lines, though atmospheric interference, spectral overlap, and peak masking currently limit their quantitative estimation. The MEIGA-n chain is validated and transferable to any geographic location, making it particularly valuable in regions without monitoring networks, such as much of Latin America, where it opens the possibility of developing locally adapted calibration strategies for CRNS-based soil moisture monitoring.