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Response functions for detectors in cosmic ray neutron sensing

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ABSTRACT

Cosmic-Ray Neutron Sensing (CRNS) is a novel technique for determining environmental water content by measuring albedo neutrons in the epithermal to fast energy range with moderated neutron detectors. We have investigated the response function of stationary and mobile neutron detectors typically used for environmental research in order to improve the model accuracy for neutron transport studies. Monte Carlo simulations have been performed in order to analyze the detection probability in terms of energy-dependent response and angular sensitivity for different variants of CRNS detectors and converter gases. Our results reveal the sensor's response to neutron energies from 0.1 eV to 10^6 eV and highest sensitivity to vertical fluxes. The detector efficiency shows good agreement with reference data from the structurally similar Bonner Spheres. The relative probability of neutrons contributing to the overall integrated signal is especially important in regions with non-uniform albedo fluxes, such as complex terrain or heterogeneous distribution of hydrogen pools.

1. Introduction

Cosmic radiation is omnipresent on Earth and produces neutrons that interact with the atmosphere [1] and the ground [2]. In the last decades, many types of moderated and non-moderated neutron detectors have been employed to observe those fluxes, such as high-energy neutron monitors [3] or Bonner Spheres [4]. Neutrons in the epithermal to fast energy range (1 eV to 10^5 eV) are highly sensitive to hydrogen, which turns neutron detectors to efficient proxies for changes of environmental water content [5]. The method of Cosmic-Ray Neutron Sensing (CRNS) [6,7] is a promising tool for hydrological and environmental applications. The CRNS probe is usually mounted 1–2 m above the ground surface, providing a significant exposure to far-field radiation from albedo neutrons which have further penetrated tens of decimeters into the soil [7,8] or snow [9]. Hence, the neutron count rate is representative for the average root-zone water content in a footprint of several tens of hectares. The developments in the last years led to an enormous success of the method [10] due to its large footprint, low maintenance, and non-invasive nature [11]. However, to date, some features of the neutron response are still unknown and thereby introduce uncertainties to the measurement. For example, the influence of vegetation [12–14], detector location [15,16], and incoming cosmic-ray fluctuations [17–19]. In the last few years, neutron simulations have been conducted to answer some of the open questions by transport modeling (e.g., [8,20–22]). In order to reduce the enormous computational effort, which inevitably goes along with the large scale differences of a $\sim$1 m^3 detector in a $\sim$1 km^3 environment, effective response models have to be applied rather than using the geometrical detector itself in the simulation. The solution to increase the recorded flux is to adequately scale up the volume of the detector entity. However, if such a detector is simulated in the domain with its actual geometry (e.g. moderator and converter tube), this significantly alters its characteristics, completely undermining this approach. A virtual sensor entity with an effective model allows for the upscaling of the counting volume of a detector, while still retaining the same features as the unscaled type. It also allows to set the maximum detection probability within the operation range to 100%. However, such neutron detection models are sensitive to the specific response function of the detector [23–25]. This property determines which neutron of which energy and from which direction is how likely to trigger an event.

The current demand for autonomous techniques that monitor the water cycle is steadily increasing, while field measurements are required to get more and more accurate. It is thus important to understand the inherit sensitivity of the neutron detector to systematic effects in the environment, such as various hydrogen pools and cosmic-ray fluctuations. An accurate description of the detector's response function is a relevant step towards the goal to assess sensor signals with the help of simulations. Within the context of cosmic-ray neutron sensing, the

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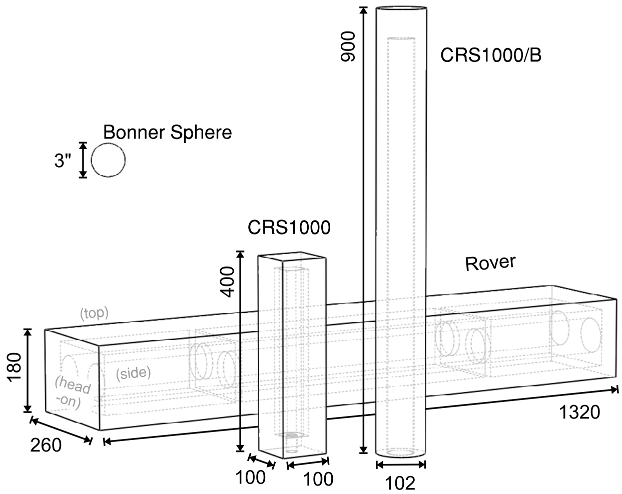

Fig. 1. Variants of the cosmic-ray neutron detectors modeled in this study. Dimensions are in units of millimeters. To scale a Bonner Sphere is illustrated in comparison.

main objective of this study is (i) to evaluate the detection characteristics of the actual CRNS probes for environmental neutron fluxes in general and (ii) to analyze relative differences between the models.

2. Materials and methods

2.1. The cosmic ray neutron probes

Cosmic-ray neutron sensors of type 'CRS'[1] are commercially available in several configurations, spanning a variety of gaseous converters, geometry and orientation, see Fig. 1. The CRS1000 and CRS1000/B are mainly used in a stationary mode to monitor environmental neutron fluxes, and the Rover system is typically used in vehicles for mobile surveys of spatial neutron distributions, for example in applications of agricultural land use [26]. A description of the main components and detection physics can be found in [11,16]. The sensors comprise one or two moderated detector tubes sensitive to epithermal/fast neutrons, a high voltage generator, a pulse height analyzer, and a data logger with integrated telemetry. As a neutron moderator, high-density polyethylene of 1 inch thickness is used to encase the proportional counter tube that is filled with a neutron converter gas. The CRS1000 uses helium-3, while the CRS1000/B uses boron trifluoride, which requires larger detectors in order to achieve the same count rate due to its lower cross section (3837 b vs. 5316 b at 25.3 meV) [27] and lower pressure (0.5 bar vs. 1.5 bar) and therefore total absorption efficiency. The Rover, introduced in [5], is technically equivalent, but consists of significantly larger detectors than the stationary sensors and two tubes in one moderated module to increase the event rate, which, as a consequence of counting statistics, allows for higher temporal resolutions (see e.g. [22,28]).

2.2. URANOS

The calculations presented here have been carried out using the recently developed code URANOS (**U**ltra **Ra**pid **N**eutron-**O**nly **S**imulation). The program, which is freely available online,[2] has been designed as a Monte Carlo simulation of neutron interactions with matter. Recent applications cover the characterization of neutron detectors for Spin Echo instruments in nuclear physics [29] and studies of cosmic-ray induced albedo neutrons in environmental physics [8,15,16,22], similar to previous studies of [7,9,30] using MCNPX [31,32] using GENAT4 [33] or [34] using PARMA [35]. The standard calculation routine features a ray casting algorithm for single neutron propagation. The physics model follows the implementation declared by the ENDF database standard and was described by OpenMC [36]. It features the treatment of elastic collisions in the thermal and epithermal regime, as well as inelastic collisions, absorption and emission processes such as evaporation. Cross sections, energy and angular distributions were taken from the databases ENDF/B-VII.1 [37] and JENDL/HE-2007 [38].

[1] Hydroinnova LLC, US.

[2] http://www.ufz.de/uranos.

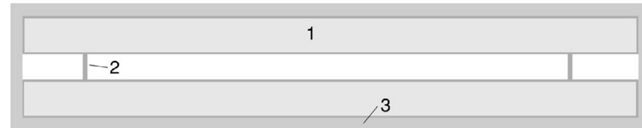

Fig. 2. Cross section of the Rover detector simulation model with a length of 132 cm and a width of 26 cm. It features two gas filled proportional counter tubes in a stainless steel casing (1), aluminum mounting brackets (2) and a HDPE moderator (3).

2.3. The detector model

URANOS handles model definitions by extruding voxels from layered images in a stack along the z dimension. The central cutout of the detector configuration used in this study is shown exemplarily in Fig. 2. The sensor geometry has been derived from actual devices and from supporting information provided by the manufacturer [39], see also Fig. 1. Details of the mechanical parts have been reduced to features that have a significant influence on the neutron response, and only materials with significant macroscopic neutron cross sections have been considered. The size of the voxels has been set to 1 mm × 1 mm × h mm, whereas h denotes the layer height to which the voxel is extruded and varies from 1 mm, the generic cubic configuration, to 850 mm for the length of the CRS1000/B tube. The materials used are: high-density polyethylene (CH_2) at a density of 0.95 g/cm^3, aluminum oxide (Al_2O_3) at 3.94 g/cm^3, steel (Fe with 20% Cr, 20% Ni) at 8.03 g/cm^3, boron trifluoride (^{10}B enriched BF_3 gas) at 2.76 kg/m^3, ^{3}He enriched noble gas at 0.125 kg/m^3, and air (78% N_2, 21% O_2, 1% Ar) at 1.2 kg/m^3. The partial gas pressure has been set to 1.5 bar for helium and to 0.5 bar for boron trifluoride.

The orientation of the simulated detector tubes reflects the operational standard in environmental applications [11]. The stationary systems (CRS1000 and CRS1000/B) are oriented upright, while the mobile system (Rover) is oriented horizontally. We further define two directions of the natural cosmic-ray neutron flux facing the 'top' and the 'sides' of the detector. Consequently, the 'top' facing flux runs from the surface upwards through the short cuboid face of the stationary sensor, and through the long cuboid face of the mobile detector. The 'side' facing fluxes run parallel to the surface through the long faces of the stationary detector and through two short and two long faces of the mobile detector. In order to simulate incoming cosmic-ray flux from the atmosphere, monoenergetic neutrons were released randomly from a virtual plane of the same extension as the model dimensions. The number of neutrons absorbed in the converter gas divided by the total number of neutrons released is defined as the *efficiency* of the setup, which intrinsically normalizes the efficiency to the detector area. The CRS1000/B consists of a proportional counter housed in a cylindrical casing. As here also the identical plane source definitions are used, this geometry leads to an ambiguity in the efficiency definition, which has to be considered for interpreting the results, see also [40]. That means, due to the surface normals being different for the cubic CRS1000 and the cylinder of the /B version, the directionality of an