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Long and short-term atmospheric radiation analyses based on coupled measurements at high altitude remote stations and extensive air shower modeling

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ABSTRACT

In this paper are described the ACROPOL and OPD high-altitude stations devoted to characterize the atmospheric radiation fields. The ACROPOL platform, located at the summit of the Pic du Midi in the French Pyrenees at 2885 m above sea level, exploits since May 2011 some scientific equipment, including a BSS neutron spectrometer, detectors based on semiconductor and scintillators. In the framework of a IEAv and ONERA collaboration, a second neutron spectrometer was simultaneously exploited since February 2015 at the summit of the Pico dos Dias in Brazil at 1864 m above the sea level.

The both high station platforms allow for investigating the long period dynamics to analyze the spectral variation of cosmic-ray- induced neutron and effects of local and seasonal changes, but also the short term dynamics during solar flare events.

This paper presents long and short-term analyses, including measurement and modeling investigations considering the both high altitude stations data. The modeling approach, based on ATMORAD computational platform, was used to link the both station measurements.

1. Introduction

The characterization of the atmospheric radiation fields is of importance since the presence of particles in the environment is ubiquitous. The knowledge of the atmospheric radiations and their dynamics are essential issues in the evaluation of the Single Event Effects [1–4], the assessment of radiation risks in aviation [5–6] and the space environment (space weather). Neutrons, protons and muons are the main secondary particles produced by the interaction of primary cosmic rays (mainly composed by proton and alpha) with the nuclei of the constituents of the atmosphere [7]. In ground environment, neutron fluxes can also be impacted by the interaction of alpha particles emitted by radon [8], by the weather condition [9–11] or by seismic activities [12–13]. Besides, cosmic and terrestrial sources, atmospheric neutrons may be also be generated by lightning discharges [14–15].

The AIR (Atmosphere Ionizing Radiation) project was initiated by *Wilson* primarily as a modeling effort. *Goldhagen* joined the group after it was initiated and his data was used as validation. The main goal was to measure the neutron energy spectrum (spectral fluence rate) at flight altitudes (10–12 km above sea level and even higher) thanks to the NASA high altitude Aircraft ER-2 [16–18]. In 1998 during a Solar Minimum, a series of flights were successfully conducted. The paths were chosen to cross various conditions in terms of geomagnetic latitudes (from 0.8 GV up to 12 GV) and altitudes (from +12 km up to +20 km). The measurements were performed with an extended range Bonner Sphere Spectrometer (BSS) made of 10 classical Bonner Spheres and two additional ones extended to high energies. The neutron spectra obtained during these experiments are very precious and are still used as references to validate atmospheric radiation codes which are developed for aircrew personal dosimetry or microelectronics reliability applications. While these data are very rewarding, they correspond to a specific phase in the Sun's activity (solar minimum). Hence, they are punctual and it would be interesting to have continuous experiments allowing for neutron spectra determination over a long-term campaign and various solar activity conditions.

The Neutron Monitors (NMs) are widely used across the world to monitor cosmic rays in the vicinity of the Earth magnetosphere. Currently, there are more than 50 neutron monitor stations located in different regions of the planet [19–21]. These stations are usually devoted to the study of cosmic-ray-induced neutron origin and some of them have been collecting data on neutron flux at ground level for many decades. More recent works are related to the characterization

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of the neutron spectrum at flight level and mountain altitude with extended-range BSSs [22–25].

Then, to study over a long period the dynamics of neutron spectrum from meV to GeV, the French Aerospace Lab. has operated a neutron spectrometer named HERMEIS [22]. This system is particularly suitable for the measurements in low fluence rate environments. The neutron spectrometer was fully tested and characterized nearby European standard calibration fields.

Thus, since 2008, the French Aerospace Lab. has developed a high-altitude platform named ACROPOL (high Altitude Cosmic Ray ONERA/Pic du Midi Observatory Laboratory) [4,26]. This platform exploits some scientific equipment, including a BSS neutron spectrometer, detectors based on semiconductor and scintillators. The objective is to characterize the atmospheric radiations and their dynamics, particularly the energy neutron spectrum. Measurements and analyses of the spectral variations of cosmic-ray induced neutron were performed over a four years period. Thus, the neutron spectrometer was installed at the summit of the Pic du Midi in the French Pyrenees at 2885 m above sea level in May 2011. One limitation of our approach is the fact that contrary to the neutron monitors which cover all geomagnetic latitudes, there is an exploited neutron spectrometer in one altitude location. Indeed, in the framework of Institute for Advanced Studies (IEAv) and ONERA collaboration, a second neutron spectrometer was exploited simultaneously since February 2015 at the summit of the Pico dos Dias (named OPD, Observatory of Pico dos Dias) depending from the LNA (National Astrophysics Laboratory) in Brazil at 1864 m above the sea level [27]. The both high altitude station platforms allow for investigating the long period dynamics to analyze the spectral variation of cosmic-ray-induced neutron and effects of local and seasonal changes, but also the short period dynamics during solar flare events.

In addition, the OPD site is located well inside an interesting region, under the South Atlantic Magnetic Anomaly (SAMA), which will allow correlate results from this region, comparing it with the ACROPOL data. This could give additional information about the dynamic of this region, especially during perturbed geomagnetic and solar conditions.

Moreover, spectrum measurement analyses can be reinforced by the atmospheric radiation model. Thus, the ATMORAD methodology was presented in previous work [28]. It bases on GEANT4 simulations [29] of Extensive Air Showers (EAS) and the solar modulation potential. Previous results [28] demonstrate the potential of using ATMORAD and cascade neutron fields to monitor the solar activity and more particular the Forbush decreases (FD) during solar events.

This paper presents long and short-period analyses of the atmospheric neutron spectrum and fluxes, including measurement and modeling investigations. Analyses were applied to the both high altitude stations and the modeling approach was used to link the both station measurements. Results investigate the ability of ATMORAD to deduce the neutron fields related to any altitude, longitude and latitude from fixed high altitude measurements.

2. Experimental platforms and modeling

2.1. High altitude station and platform descriptions

The neutron radiation field characterizations (spectrum) are simultaneously performed at the top of the Pic-du-Midi and OPD stations, Table 1 summarizes the characteristics of these two stations. Both stations are installed in well controlled experimental areas, with controlled temperature and humidity.

The neutron environment is measured at the both stations using the HERMEIS system [22] based on *Bonner multi-spheres*. It was developed by the IRSN Laboratory of Neutron Metrology and Dosimetry and the Space Environment Department of ONERA which has installed this spectrometer to study the dynamics of the energetic distributions, from meV to GeV, of cosmic-ray-induced neutrons. Fig. 1 presents a picture of the both stations.

Table 1
Characteristics of both altitude stations.

	Pic-du-Midi, France	Pico dos Dias, Brazil
ACRONYM	ACROPOL	OPD
Altitude (m)	2885	1864
Latitude	42°55′N	22°32′S
Longitude	0°08′E	45°34′W
Cut-off rigidity	5.6 GV	9 GV
Neutron flux relative to New York City	8.5	3
Neutron experiment	Neutron spectrometer	Neutron spectrometer Ionization chamber Liulin
Start operating	May 2011	February 2015

Fig. 2 presents the neutron spectrometers installed in the both stations, the Liulin detectors and the ionization chambers. The neutron spectrometer consists of 10 homogeneous polyethylene (PE) spheres with increasing diameters (3″, 3.5″, 4″, 4.5″, 5″, 6″, 7″, 8″, 10″ and 12″). The high pressure (10 atm.) ^{3}He spherical proportional counter (2″) placed in the center of the spheres allows high detection efficiency.In addition, the spectrometer includes two PE spheres with inner tungsten and lead shells (8″ and 9″, respectively) in order to increase the response above 20 MeV. The counts given by each sphere are automatically stored every five minutes with the mean meteorological conditions. Then, in previous works, the fluence responses were calculated and the method that allows for deducing the spectrum from detection levels was developed. In this work, the method used to derive the spectral fluence from a set of readings consisted in using a well-established code based on iterative convergence algorithm. The GRAVEL unfolding code requires a priori information about the neutron spectrum which is an estimation of the shape of the neutron spectrum at the measurement location [30]. This "default spectrum" is needed to start the procedure and then GRAVEL iteratively adjusts the neutron fluence distribution based on the readings and the response matrix. After a number of iterations defined by the user or as soon as the fluence distribution is consistent enough with the readings, the process is stopped. The relative uncertainties of the detector counts are used as weighting factors during the iteration process.

Moreover, a silicon energy deposition spectrometer named Liulin [31] and an ionization chamber were operated in the OPD, close to the neutron spectrometer. Liulin detector is commonly used to characterize radiation fields on board aircraft. Liulin is an active detector with a silicon diode as the sensitive volume and it can measure energy deposition spectra, fluxes and dose in mixed radiation fields. The ionization chamber, from Thermo Scientific, model FHT 192, collect the data every 5 min by means of an electronic detector Thermo Scientific, model FH 40 G and the data is registered by a connected computer. The data is based on collection of charges created by direct ionizations within a gas. It only uses the discrete charges created by each interaction between the incident radiation and the gas. This both detectors (Liulin and Ionization Chamber), shown on Fig. 2, are complementary to the neutron spectrometer and can be used to investigate the long and short period dynamics of radiation fields.

2.2. Modeling based on ATMORAD

In previous works [28], Hubert et al. presents a new atmospheric radiation model named ATMORAD based on GEANT4 simulations of extensive Air Showers according to primary spectra which only depend on the solar modulation potential (Force-Field Approximation [32–33]). Based on neutron spectrometry (ACROPOL measurements), the solar modulation potential can be deduced from cascade neutron fluxes and ATMORAD.