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Analyses of cosmic ray induced-neutron based on spectrometers operated simultaneously at mid-latitude and Antarctica high-altitude stations during quiet solar activity

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ABSTRACT

In this paper are described a new neutron spectrometer which operate in the Concordia station (Antarctica, Dome C) since December 2015. This instrument complements a network including neutron spectrometers operating in the Pic-du-Midi and the Pico dos Dias. Thus, this work present an analysis of cosmic ray induced-neutron based on spectrometers operated simultaneously in the Pic-du-Midi and the Concordia stations during a quiet solar activity. The both high station platforms allow for investigating the long period dynamics to analyze the spectral variation and effects of local and seasonal changes, but also the short term dynamics during solar flare events. A first part is devoted to analyze the count rates, the spectrum and the neutron fluxes, implying cross-comparisons between data obtained in the both stations. In a second part, measurements analyses were reinforced by modeling based on simulations of atmospheric cascades according to primary spectra which only depend on the solar modulation potential.

1. Introduction

The primary and the secondary radiation produced in the atmosphere can be a serious issue for the reliability of microelectronics devices embedded in aircraft [1–4] and this is of a major concern for aircrew member's dose assessment [5,6]. Moreover, Polar Region development induces an important issue related to 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].

Many neutron detectors are distributed around the earth, especially in the Polar Regions. The Neutron Monitors (NMs) are used across the world to monitor cosmic rays in the vicinity of the Earth magnetosphere. In fact, these instruments are designed to measure and record the count rates induced at ground level by secondary radiation generated by atmospheric cascades (initiated by relativistic H or H nuclei of which kinetic energy is greater than 450 MeV/nucleon). The main contribution (95%) in the NM count rates is attributed to cosmic-ray induced neutrons. Besides, secondary muon or proton component represents a considerable amount. Currently, there are more than 50 neutron monitor stations located in different regions of the planet [8–10]. Moreover, NMs were exploited in Antarctica, at Amundsen-Scott and McMurco stations [11,12]. Unlike the Bonner Sphere Spectrometers (BSSs), the NM count rates provide information on the relative variation of the Galactic Cosmic Ray (GCR) intensity, however various techniques related to the multiplicity or details on the timing of neutrons originating in the lead allow limited spectral resolution [13].

Thanks to combined analyses of the count rates of NMs located at various geomagnetic coordinates (vertical cut-off rigidity), precious information about primary GCR energetic spectrum and its angular distribution can be investigated [14]. The time variation (i.e. dynamics) can also be investigated with a very interesting time resolution (down to 5 or 1 min) which allows for observing Forbush Decreases (FDs) or Ground Level Enhancements (GLEs) after strong solar events. However, neutron monitor register the neutron flux (i.e. counts), and the energy of the incident neutrons cannot be determined.

Complementary works are related to the characterization of the neutron spectrum at flight level [15–17] and mountain altitude with extended-range BSS [18–20]. Recently, a neutron spectrometer network composed by three high altitude stations was developed by the French Aerospace Lab thanks to an advanced BSS extended to high energies. This instrument can measure the neutron spectrum over a wide energy range from meV up to tens of GeV with a short time resolution allowing to investigate the both solar

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flare events and the seasonal variations. Two high altitude stations were implemented in the Pic-du-Midi and in the Pico dos Dias [21], in May 2011 and January 2015, respectively. Long and short-period analyses of the atmospheric neutron spectrum and fluxes were presented from measurements performed in the Pic-du-Midi and in the Pico dos dias stations. Short-period analyses were detailed for the both solar event, in August 2011 and March 2012, respectively. The FDs are clearly distinguishable and this work proposed analyses based on physical parameters describing the transport of CME in the heliosphere. Analyses were reinforced by the atmospheric radiation model (ATMORAD, ATMOspheric RADiations [22]) based on GEANT4 simulations [23] of atmospheric cascades and the solar modulation potential.

More recently (i.e. in December 2015), a new neutron spectrometer was installed in the Concordia station in Antarctica, in the framework of the CHINSTRAP polar project (Continuous High-altitude Investigation of Neutron Spectra for Terrestrial Radiation Antarctic Project). The geomagnetic conditions (∼0.001 GV) and the high altitude (3233 m above the sea level) of Concordia let us observe solar particle events such as Forbush Decreases (FD) or Ground Level Enhancement (GLE).

The main objective of this paper is to analyze the cosmic ray induced-neutron based on spectrometers operated simultaneously at medium latitudes (mainly in the Pic-du-Midi station) and at the high altitude Antarctica station. A first part is devoted to analyze the count rates, the spectrum and the neutron fluxes, implying cross-comparisons between data obtained in the both stations. In a second part, measurements analyses were reinforced by ATMORAD modeling.

Table 1
Operational spectrometers characteristics.

	Detector		
	PEHD (high density polyethylene)	Metallic shell	Integ. time
Pic-du-Midi	3″, 4″, 7″, 10″, 12″	9″ lead, 8″ tungsten	5 min
Pico dos Dias	3″, 5″, 8″, 12″	9″ lead, 7″ tungsten	
Concordia	3″, 5″, 8″, 12″	9″lead, 7″ tungsten	
Toulouse	3″, 4″, 12″	9″ lead	

Table 2
Characteristics of Pic-du-Midi and Concordia Stations.

	Pic-du-Midi, France	Concordia station, Antarctica
ACRONYM (Lab., project)	ACROPOL	CHINSTRAP
Altitude	2885 m	3233 m
Latitude	42°55′N	75°06′S
Longitude	0°08′E	123°19′E
Cut-off rigidity	5.6 GV	< 0.001 GV
Atmospheric depth	700.7 g/cm^2	635 g/cm$'^2$
Neutron experiment	Neutron spectrometer CCD camera Muon scintillator	Neutron spectrometer
Start Operating	May 2011	December 2015

2. Experimental platforms and modeling

2.1. Instrument descriptions

A Bonner multi-sphere neutron spectrometer extended to high neutron energies was developed in the framework of collaboration between the Laboratory of Neutron Metrology and Dosimetry and the Space Environment Department of ONERA [18]. BSS was used to measure and investigate the energy spectrum of the cosmic-ray induced neutrons, considering the energy range from meV to GeV.

As detailed in [18], this system was composed of spherical 3He proportional counters. The counters were 5.07 cm in diameter, and filled with 10 atmosphere 3He gas. Each counter was surrounded with spherical PEHD (high density polyethylene) moderators with different thicknesses. Additionally, the spectrometer includes two PEHD spheres with inner tungsten and lead shells (7/8″ and 9″, respectively) in order to increase the response to neutrons above 20 MeV.

Electronic part dedicated to drive each signal, was composed to the pre-amplifier and the linear amplifier. The output pulse signals were introduced to a Multi Channel Analyzer (MCA) to be converted into the pulse height spectra or/and to a multi counter to integrate the count rate during the integration delay (generally considered equal to five minutes). The total counts of each detector were obtained by summing the total counts over a given integration time. The response functions (deduced from GEANT4 and/or MCNPx calculations) were used to convert the measured counting rates to neutron energy spectrum.

2.2. High altitude stations and platform descriptions

Actually, three spectrometers are operational. The Table 1 details the spectrometers characteristics, i.e. the detector types and sizes (PEAH and metallic detectors) and the integration time.

Indeed, since 2008, the French Aerospace Lab. has developed a high-altitude platform named ACROPOL (high Altitude Cosmic Ray ONERA/Pic du Midi Observatory Laboratory). This platform exploits some scientific equipment, including a BSS neutron spectrometer, detectors based on semiconductor and scintillators. ACROPOL laboratory was fully presented in previous papers [4,22]. Thus, the first 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.

A second neutron spectrometer was exploited simultaneously since February 2015 at the summit of the Pico dos Dias (Observatory of Pico dos Dias) depending from the LNA (National Astrophysics Laboratory) in Brazil at 1864 m above the sea level.

The geomagnetic cut off rigidity of the Pic-du-Midi and Pico dos Dias observatory are respectively 5.6 and 9 GV. To investigate the time dependence of the local cosmic-ray induced neutron spectrum with respect to the variation of the primary galactic cosmic rays reaching the Earth magnetosphere (space weather), it is necessary to collect data at locations where the value of the geomagnetic cut off rigidity is slightly different. Typically, at the poles, the geomagnetic cut off rigidity is 0 GV. This low value is interesting because primary particles of each energy (even the lowest coming from specific solar events) are able to penetrate in the atmosphere.

In the framework of the CHINSTRAP project support by IPEV (French Polar Institute), a new neutron spectrometer composed by six spheres was installed at Concordia research station (Antarctica). This new instrument significantly expands the capability of the present neutron spectrometer network (composed by the Pid-du-Midi and the Pico dos Dias stations). The station is located at Dome C on the Antarctic Plateau (75°06′S, 123°23′E, Fig. 1) at height of 3233 m above the sea level. The site has an almost zero rigidity cutoff (R < 0.01 GV), i.e., no geomagnetic shielding even for low-energy particles. Thus, the Fig. 1 presents an overview of the Concordia research station, the scientific shelter and the neutron spectrometer operated since December 2015 (altitude, latitude and longitude are given in Table 2).

Moreover, a new cosmic ray detector has been installed in the physics shelter (close to the atmospheric shelter) in Concordia station since 2015 [58]. This detector consists of two mini