The Solar Neutron TRACking (SONTRAC) Instrument for the Detection of Fast Neutrons

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***Abstract*—Fast neutrons (energies >0.5 MeV) contribute to the radiation exposure of space hardware and astronaut crew, enable greater understanding of planetary atmospheric and surface compositions and allow unique measurements of solar particle acceleration. Neutrons are challenging to detect and measurements of them typically suffer from high background rates. High-energy neutrons (>50 MeV) pose even more challenges, because the traditional double-scatter technique based on a time-of-flight (ToF) measurement. These measurements are challenging due to size constraints on satellites, particularly newer small satellites. The SOlar Neutron TRACking instrument (SONTRAC) is a small satellite neutron detector that utilizes fine-grained scintillating fiber bundles with 1-mm pitch silicon photomultiplier (SiPM) array readout. Signal processing is accomplished with multi-channel ASICs. SONTRAC is able to image fast neutron (between 20-200 MeV) scatters in a compact scalable package. We discuss below the numerous applications of this technology and recent progress on the development and performance characteristics of the prototype instrument.**

I. Introduction

FAST neutrons (>0.5 MeV) and γ rays play an important role in characterizing the radiation exposure on and near planetary bodies, in mapping atmospheric and surface composition, and in understanding particle acceleration processes. Unlike γ rays, fast neutrons are detectable only from the Sun, planets, and the Moon due to the 881-s neutron lifetime. Measurements of solar neutrons improve our understanding of particle acceleration at the Sun, while the detection of locally produced albedo neutrons (interacting with planetary atmospheres or the surface) inform us of the effect of solar eruptive events on the local radiation environment. Furthermore, constraining models of particle acceleration ultimately improves our ability to forecast space weather both at Earth and at other planets. It also helps us understand the effect of our young Sun (and other host stars) on climate and habitability of exoplanets (Airapetian et al. 2019).

Improved knowledge of the Earth's atmospheric neutrons themselves, including spatial and temporal variations, are valuable because neutron-induced single event upsets in avionics systems constitute a reliability problem. Furthermore, neutrons are penetrating, dangerous and abundant, posing a health and safety risk to astronauts and aircraft personnel. Neutrons also pose a major background for other NASA assets (Ormes et al. 2007).

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II. Solar Neutron Tracking Concept

Observations of fast neutrons can be achieved using compact, low-power detectors placed in LEO on small satellite platforms such as CubeSats. Deep-space probes to the inner Heliosphere (Woolf et al. 2009; de Nolfo et al. 2019a,b) would be even more valuable for solar-neutron measurements, and would have similar constraints as CubeSats on instrument mass, volume, and power. An ideal detector configuration for small satellite opportunities would be to make use of all the potential volume available for the instrument, thereby significantly increasing the detection efficiency in the solar neutron energy range measured at Earth. This can be accomplished by detecting double neutron scatters in a single large volume and imaging the tracks of the recoil particles (within scintillating fibers). Replacing the traditional Time-of-Flight (ToF) measurement of double scatter neutron detectors are the measurements of the recoil position and momentum vectors which provide more imaging information, specifically collapsing the classical Compton telescope annulus to the equivalent of a small annulus segment, greatly reducing the incident neutron solid angle, and with it background.

The SOlar Neutron TRACking (SONTRAC) instrument consists of a 35x35-cm^2 fiber bundle with orthogonally stacked, alternating layers of parallel scintillating plastic fibers with a pitch of 1.36-mm that mates directly to SiPM arrays of similar pitch (de Nolfo et al., 2019a,b; Suarez et al., 2019), see Figure 1 (left & middle panels). The current SONTRAC prototype has a pitch larger than that ultimately desired, but provides a good proof-of-principle instrument. Scintillating fibers are readout by 1-mm^2 SiPM arrays from KETEK, with <1-ns rise times, that can be manufactured with a pitch a few-hundred μm, offering, for the first time, a viable option for neutron spectroscopy and imaging based on high-resolution charged-particle tracking.

New simplified analog signal processing techniques have been developed to convert 2-d information into two 1-d projections (for the x-z face) thus reducing the readout complexity without a significant loss in measurement accuracy (e.g., Belcari et al. 2007 and references therein). SONTRAC's fine grain SiPM arrays are read out in four 1-d strips (summed

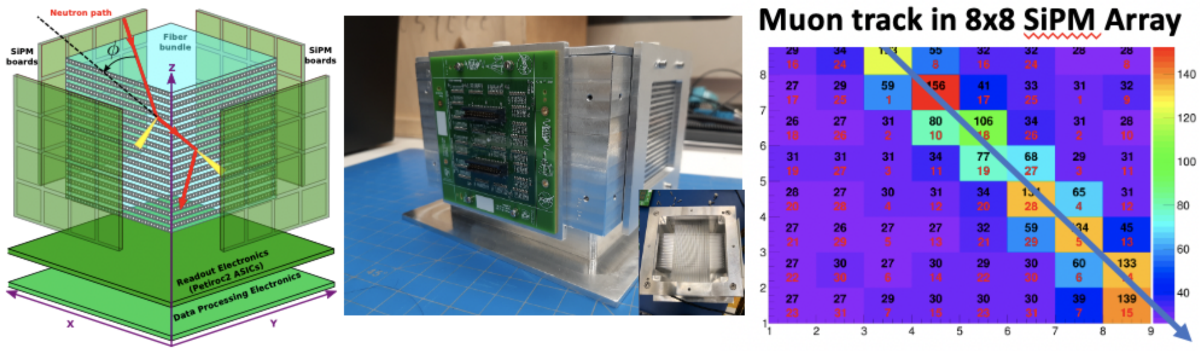

Fig. 1. (Left) SONTRAC Concept with two neutron scatters (red) and track imaging (yellow) with orthogonally stacked plastic scintillators readout by arrays of SiPMs. (Middle) SONTRAC prototype, (Right) Muon track through center of SONTRAC fiber bundle.

SiPMs along individual strips) rather than in the form of numerous individual SiPMs, significantly reducing the number of channels to process, i.e., several 1-d projections, as opposed to 2-d stereoscopic images. Three orthogonal projections unambiguously describes a track (Ryan et al. 2003). Further details of the strip configuration for SONTRAC are discussed in Suarez et al., these proceedings.

For a small satellite (e.g. CubeSat), 128 channels is still a large number to be read-out with discrete electronics. To address this, the signal readout for the prototype SONTRAC utilizes a CAEN DT5550W readout system with Petiroc2A ASICs. The 32 channel Petiroc2A ASIC processes the signal from each of the SiPM detector strips. The DT5550W has a field programmable gate array (FPGA) that can be used to test the hardware-based track recognition algorithms in combination with the strip readout.

A SiPM-based neutron imaging spectrometer is a significant improvement over earlier proton-tracking based technologies (Ryan et al. 1999; Miller et al. 2005; Legere et al. 2006; Muraki et al. 2012; 2013). Yamaoka et al. (2018) recently proposed a CubeSat Neutron Sensor (CNS) using SiPM readout coupled to a fiber block. SONTRAC offers better spatial resolution (1.36 mm as apposed to 4-mm) and much greater data compression based on our novel strip readout technique.

III. PERFORMANCE & SUMMARY

We have tested the single anode and strip configurations of SONTRAC using ground level muons to confirm that the response of 1-mm fibers viewed by individual SiPMs is indeed sensitive to minimum ionizing particles as well as to demonstrate the capability to readout muon tracks. Figure 1 (right panel) shows a muon track obtained from SONTRAC viewed by a 8x8 array of 1-mm SiPMs and individually readout by the DT5550W readout system. Muons are identified by a one-inch coincidence scintillating paddle above the bundle. The variation in signal pulse height (see color scale value in the SiPM array) is a result of the trajectory of the muon passing through different cross sections of the fibers. Preliminary laboratory sources were used to establish a minimum threshold for a 1-mm pitch configuration of 60 keVee corresponding to 180 keVpe proton equivalent. These tests show that individual SiPMs can easily trigger on the several photoelectrons expected from a minimum ionizing particle (MIP) in $\sim$1-mm fibers. The large dynamic range allows the proton-recoil Bragg peak to be recognized. The 1.36-mm pitch of the current array imposes a minimum proton energy of 25 MeV for tracking, or a double scatter neutron threshold of 50 MeV, although lower thresholds ($\sim$10 MeV) are possible with smaller fiber pitch. Track reconstruction using ground-level muons is discussed in detail in Suarez et al., these proceedings. Simulations give a detection efficiency for registering proton recoils within SONTRAC of $\sim$200 mm^2 for single scatters and $\sim$2 mm^2 for double scatters at 60 MeV.

The SONTRAC instrument is scalable to suit different science applications within a SmallSAT platform. For example, a (10 cm)^3 neutron tracker, surrounded by charged particle anti-coincident detector, could readily fit into a 3U CubeSat. A 10-cm^3 SONTRAC would have an effective area for detecting 15-60 MeV neutrons of 2 cm^2, approximately the neutron effective area of the 1.5-ton imaging Compton telescope, COMPTEL. A CubeSat instrument would be far more sensitive due to the small spacecraft background due to the spacecraft's small mass. Larger versions of the fiber-based neutron spectrometer are possible such that an entire 4U could be dedicated to scintillating fibers and readout (perhaps by assembling small blocks), significantly improving the effective area. Future plans include an accelerator beam test scheduled for October 2020 and a high-altitude balloon-borne opportunity for SONTRAC in late 2023.

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