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

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***Abstract*—The detection of fast neutrons has important applications in several fields including solar, geospace and planetary physics. 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 is limited by short flight paths and small detector sizes characteristic of small satellite platforms. It is now possible to perform high-energy neutron measurements inside a large monolithic detector by imaging the recoil proton tracks, thus eliminating the need for a measure of the time-of-flight. The concept is based on a spectrometer assembled from numerous thin hydrogenous scintillating fibers that allow ionization track imaging. Fine grained readout is now possible with arrays of 1-mm pitch silicon photomultipliers (SiPMs). The Solar Neutron TRACking (SONTRAC) instrument, equipped with scintillating fibers readout with SiPMs sensors, provides high-resolution, fine grained, imaging of fast (between 20-200 MeV) neutron scatters in a compact, low-power design ideal for small satellite (and aircraft) platforms. We discuss below applications of this technology and performance characteristics of the prototype SONTRAC instrument.**

I. INTRODUCTION

NEUTRAL radiation plays an important role in understanding the energetics of solar eruptive events in addition to space weather both at Earth and at other planets. After neutrinos, the rarest and most difficult measure of solar flare particle acceleration is the spectrum and emission-time-profile of secondary neutrons (Lingenfelter et al. 1965). They constitute the only efficient and direct neutral particle channel for energetic ion interactions from 50 to 300 MeV. This mid-energy range fills a gap between the nuclear -ray lines at lower energies and the high-energy rays from pion decay. A solar neutron measurement from 20-200 MeV would be an important measurement when combined with high- and low-energy -ray measurements. In this range, neutron survival to 1 AU is likely, and is coincidentally the best range to fully sample a wide swath of the energetic ion population. Furthermore, the dominant source of the inner radiation belt protons near 100 MeV arises from the decay of secondary neutrons produced in the Earths atmosphere (Singer 1958; Jentsch 1981; Selesnick et al. 2007).

In addition to the above applications, improved knowledge of atmospheric neutrons themselves, including spatial and temporal variations, are valuable because neutron-induced single event upsets in avionics systems constitute a reliability problem (Leray 2007). Furthermore, neutrons are penetrating, dangerous and abundant, posing a health and safety risk to astronauts and aircraft personnel (Dyer 2002). Neutrons also constitute a major background for other NASA assets in LEO (e.g., Wunderer et al. 2006; Ormes et al. 2007). SONTRAC will provide a compact, low-mass, low-power neutron detector enabling opportunities to detect Heliospheric neutrons on small satellites and/or deep-space probes.

II. SOLAR NEUTRON TRACKING CONCEPT

The neutron/γ-ray spectrometer, SONTRAC, first conceptually introduced by Glenn Frye et al. (1985), provides a means to measure neutrons in the range of 20-150 MeV in a compact envelope with high efficiency, ideal for a small spacecraft. The SONTRAC concept relies on the measurement of the momentum vector of the recoil proton associated with two interactions within a single scattering volume, e.g., the highly segmented fiber bundle. From a measure of the recoil moment in two successive scatters, the energy and direction of the incident neutron can be readily reconstructed (Fig. 1). A system that measures the parameters of both recoil proton tracks in 3-d, provides the necessary and sufficient information to determine the incident neutron energy and direction with no azimuthal ambiguity (Ryan et al. 1993, 2012). The angular and energy resolutions depend on the ability to accurately

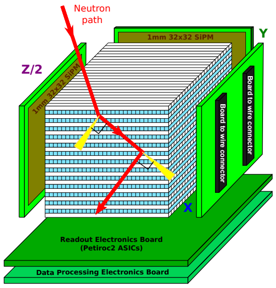

Fig. 1. SONTRAC instrument consisting of orthogonally stacked plastic scintillators readout by arrays of SiPMs. A measurement of two recoil tracks from fast neutron interactions determines the incident neutron energy and direction.

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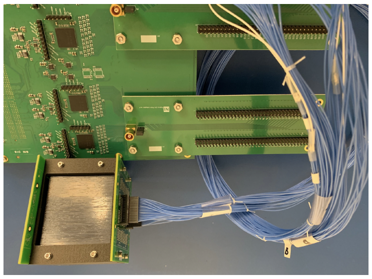

Fig. 2. SONTRAC instrument prototype showing scintillating fiber bundle readout on two sides by 32x32 arrays of 1-mm SiPMs.

measure the proton tracks. Imaging allows for a more complete separation of the source signal from the background. By allowing the scatter to take place in a single large block, the solid-angle factor between the scatters is much greater than that for widely separated detectors utilizing the time-of-flight technique, increasing the efficiency. As such, it would have wide fields of view, front and back.

SONTRAC was originally developed for the study of high-energy solar flare processes, but it was expanded to atmospheric physics, radiation therapy, and nuclear materials monitoring (Bravar et al. 2005). Because the original SONTRAC was based on scintillating fibers readout by image intensifiers with CCD detectors, the concept exhibited limitations including slow event rate, large data volume and large physical size/mass (Ryan et al. 2003). The upgraded SONTRAC (discussed in this paper) consists of orthogonally stacked, alternating layers of parallel scintillating plastic fibers read out by arrays of silicon photomultipliers (SiPMs), see Figures 1 and 2. SiPMs, with $<$1-ns rise times, good quantum efficiency, and low noise, offer a compact, robust, low-power readout. Commercial arrays of 1-mm SiPMs with a pitch of 1.36 mm are readily available (e.g., KETEK), however, custom SiPMs can be manufactured with a pitch down to several-hundred μm (e.g., smaller SiPMs can be fabricated at Fondazione Bruno Kessler). 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. 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 (see discussion below).

Individual SiPMs can easily trigger on the several photoelectrons expected from a minimum ionizing particle (MIP) in 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 (10 MeV) are possible with smaller custom SiPMs.

SONTRACs finely grained SiPM array is read out in three 1-d anode strips rather than in the form of numerous individual anodes, significantly reducing the number of channels to process, i.e., several 1-d projections, as opposed to 2-d stereoscopic images (see Fig. 2). Signal readout for the prototype SONTRAC utilizes the Petiroc2A (https://www.caen.it/products/dt5550w/), a 32-channel readout ASIC to process the incoming signal from the each of the SiPM detector strips. The Petiroc2A ASIC reduces the size, mass and power while still processing a large number of channels at a high rate. Details of the SONTRAC readout are described in Suarez et al. 2019.

III. PERFORMANCE & SUMMARY

The SONTRAC prototype has been integrated and is currently undergoing tests using ground level muons, radioactive sources, including a DT generator and Cf-242. Evaluation of the ionization energy loss along the recoil proton tracks will be compared with GEANT4 simulations in order to properly identify the Bragg peaks. Track reconstruction using ground-level muons will be used to evaluate the energy and angular response performance. Accelerator tests are planned for 2020.

We envision an instrument that is scalable to fit in either a 3U/6U or 12U CubeSat platform, depending on the science requirements, e.g. a (10-cm)^3 neutron tracker, surrounded by charged particle anti-coincident detector, could readily fit into a 3U CubeSat. Such a proposed instrument 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, because of its small mass, would be far more sensitive due to the small spacecraft background. We estimate the typical energy resolution of 10% or better for the majority of neutron events. The angular resolution is determined by the pitch of the fibers, which translates to the uncertainty in the end points of the particle tracks. For a 45 scatter and 300-m fiber pitch, it ranges from 23 at 20 MeV to 5 at 50 MeV to 0.7 at 200 MeV. This good angular resolution yields a high signal to noise and thus good sensitivity. 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.

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