BLOSM: Boron-based large-scale observation of soil moisture: First laboratory results of a cost-efficient neutron detector

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A newly developed Boron-based Large-scale Observation of Soil Moisture (or BLOSM) system is currently being tested and implemented. The stationary system provides a cost-effective way to measure fast and thermalized neutrons by using low-cost, non–hazardous and accessible materials and equipment. BLOSM operates by measuring cosmic-ray induced neutrons and by comparing the amount of fast neutrons with the amount of thermal neutrons. Fast neutrons are moderated by hydrogen atoms in the air, organic materials, and especially and primarily by water in the soil, causing the ratio between fast and thermal to be a strong indicator of soil moisture content. The fast/thermal ratio is representative for soil moisture a scale of about 30 hectares, while standard soil moisture measurements are representative for less than a square meter. This is a well-established fact but present neutron detectors are very costly. Thanks to the low-cost of the probe, BLOSM can eventually be applied at a large scale and significantly increase the number of soil–water data points thereby enabling improvement of existing hydrology models as well as new applications such as monitoring fire hazards and agricultural droughts. Here, we present the build and first tests in the laboratory. We show that BLOSM can indeed measure fast and thermal neutrons, which opens the way to applications outside the laboratory.

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Specifications table

| Hardware name | BLOSM: Boron-based Large-scale Observation of Soil Moisture |
|---------------|------------------------------------------------------------|
| Subject Area  | Environmental, planetary and agricultural sciences         |
| Hardware type | Field measurements and sensors                             |
| Closest commercial analog | The COsmic-ray Soil Moisture Observing System (COSMOS).https://cosmos.ceh.ac.uk/ |
| Open source license | CERN Open Hardware License (OHL) |
| Cost of hardware | <$1000 |
| Source file repository | https://dx.doi.org/10.17605/osf.io/jgrm8 |

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1. Hardware in context

Soil moisture content is a critical part of hydrological models used to optimise water management and agricultural productivity as well as to produce meteorological forecasts and events like floods, agricultural droughts and forest fires. Standard soil moisture probes are only valid at very small scales of a few decimetres. Soil-moisture measurements at hectometre scale are a missing link in the calibration of hydrological models and satellite measurements, which are typically at scales from tens to thousands of metres. Ideally, a large number of large-scale detectors would be installed to provide sufficient soil moisture data-points to significantly improve current hydrological models.

Our atmosphere is continuously bombarded by cosmic rays, each one causing a shower of sub-atomic particles, such as muons, pions, neutrons, protons, and photons, raining down on the Earth’s surface [21]. Muon detection cost was one of the inspirations for the present work [1]. At the Earth’s surface, 95% of the particles are neutrons [21]. When just produced, these neutrons travel very fast (15,000 km/s) but while they bounce off nuclei, they lose kinetic energy and come into thermal equilibrium. Thermal equilibrium means that the impulse of the neutrons is more or less equal to the impulse of regular atoms, which implies speeds of about 2 km/s. Different substances have different efficiencies with which they slow down fast neutrons but hydrogen rich substances, such as water, are very good at thermalising neutrons. The wetter the environment, the higher the ratio of thermal to fast neutrons will be. Given the speed of neutrons, this ratio depends on a relatively large footprint with a radius of about 300 m [22]. This relation has been known to exist since the 1960s and is being used operationally by hydrologists also for quite some time [4]. It should be noted that there are no detectors for fast neutrons that can be used in the field. There are detectors that detect thermal neutrons. By enclosing one detector in a moderating medium that is rich in hydrogen, fast neutrons will be slowed down enough to become detectable. In our case, we encase one detector in high-density polyethylene (HDPE).

Detectors using cosmic-ray neutron sensing (CRNS) have shown to be able to acquire these hectometer-scale measurements [22]. However, due to the high costs of current CRNS soil-moisture detectors, installing them in large numbers is problematic [22,18]. The main bottleneck is that these sensors are based on helium-3, which is very expensive and, as a by-product of the storage of nuclear warheads, is becoming ever rarer [8]. Here, we have developed an alternative that is cost-effective and could, once it has been tested in the field, be used to cover large areas.

Before we describe our solution, we need to mention neutron probes that are also used to measure soil moisture [2]. Neutron probes carry a source of fast neutrons, typically a mixture of americium and beryllium. It also has a boron trifluoride thermal neutron detector. The complete probe is lowered into an aluminium tube and, at different depths, the number of thermal neutrons is counted. The wetter the soil, the more fast neutrons will be slowed down and come back to the probe, where they can be detected. When used properly, the neutron probe is very useful but its footprint is still very limited to a few decimetres.

We describe a Boron-based Large-scale Observation of Soil Moisture (BLOSM) system that does not involve present disadvantages for CRNS detectors, like high-costs, use of toxic or enriched materials, and need for advanced electronics. Recent developments in silicon-based photomultipliers are combined with well-known neutron sensitive materials to achieve a low-cost neutron detector. A total expenditure below $1000 for two detectors (thermal and fast) offers the possibility of large-scale implementation while still making use of the advantages of CRNS.

2. Hardware descriptions

There are a number of nuclei that have a large cross-section for thermal neutrons and are, therefore, good at capturing them. Especially helium-3, lithium-6 and boron-10 are good at capturing neutrons. For BLOSM, we chose natural boron nitride (\(^{10}\text{BN}\)) or BN as a neutron capture agent and silver-doped zinc sulfide (ZnS:Ag) as a scintillator [11,12]. As opposed to pre-existing CRNS soil moisture detectors, BLOSM does not use toxic, flammable, hygroscopic, high-cost, or enriched materials [22,15,18]. The advantage of using natural boron in comparison to the commonly used enriched isotopes like Boron-10, Lithium-6 or even He-3, is a significantly lower-cost, ease of acquisition, import and export. Only 20% of natural Boron consists of the neutron absorbing Boron-10 isotope [16]. To compensate for this loss of neutron absorbing efficiency in comparison to enriched Boron-10 the sensitive area to capture neutrons has to be relatively large, which is not really a problem for our application. The neutron is captured by a boron-10 nucleus, which, in turn, decays into a lithium-7 and an alpha particle:

\[
^{10}\text{B}_{(0)} + ^1\text{n} \rightarrow ^4\text{He}_2 (\alpha) + ^3\text{Li}_7 + 2.38 \text{MeV}
\]

The Boron-nitride (BN) is mixed with ZnS:Ag, a scintillator with a high light yield when interacting with the alpha radiation released after a Boron-10 atom absorbs a neutron [19]. ZnS:Ag is a well-known scintillator with a slow response allowing for slower, and therefore, more economical electronics [17,7]. Another advantage of ZnS:Ag is the clear difference in response to a neutron and a gamma which facilitates the Pulse Shape Discrimination (PSD) and makes identifying neutrons easier [17]. When an alpha particle hits a ZnS:Ag particle, typically up to 170,000 blue and UV photons are produced [14].

Both BN and ZnS:Ag are white powders so a binder material is used in order to bind them together. Here Kraton (D1161) is used because it is transparent and easily dissolved in white spirit. This will result in a paint-like substance and can be applied as such. The paint will result in an almost opaque mixture which limits the maximum thickness of the material.
at approximately 0.25 mm in order to allow photons to escape the layer \[12,11,6\]. The paint is applied to a film of reflective foil to reflect photons escaping from the back side and increase light collection.

Whenever a scintillation occurs and the emitted light escapes the layer, the light needs to get to the Silicon Photomultiplier sensor (SiPM) \[5\]. The light is faint and the SiPM is small (6 mm \( \times \) 6 mm) so wavelength-shifting fibers are used as a method of light transport. The fibers are placed directly on the paint surface parallel to each other with both ends connected to the SiPM. The scintillation light is absorbed by a fiber with pigments that shift incoming light to light with a lower wavelength that stays inside the fiber core. Due to the smaller angle of total reflection, a portion of this light is trapped in the fiber and will reach the ends of the fiber where it is connected to the SiPM. The cost of a SiPM is significantly lower than a conventional photomultiplier but the sensitive area is limited (6 mm \( \times \) 6 mm). Fortunately, the small diameter (1 mm) of the wavelength shifting fibers makes it possible to connect 18 fibers to the SiPM with both ends.

Due to the large area needed and the large attenuation length (\( >3 \) m) of the WSL fibers \[10\] the optimal geometry of the sensitive material is in fact a very long strip, or ribbon. This ribbon can be coiled up to decrease the size of the detector. The coiled up ribbon together with the SiPM are positioned in a cylindrical light-tight and air-tight casing made out of aluminium (1 mm wall thickness) for the bare detector or HDPE (2.5 cm wall thickness) for the moderated detector. A general schematic of the set-up is shown in Fig. 1.

The detector is able to detect neutrons as well as gamma radiation. The signal readout can be carried out by a device with an ADC frequency of at least 200 MHz. This allows easy distinction between gamma rays and neutrons using Pulse Shape Discrimination. During the prototype phase of BLOSM, a Picoscope 2204A and a laptop were used for data acquisition and processing, later a custom PCB and a Raspberry Pi (raspberrypi.org) were used to replace both devices. The processing of data is straightforward and will result in a simple count of neutrons and gamma’s.

- The ratio of fast and thermal neutrons can be used for large area (\( \sim 300 \) m radius) soil-moisture measurements. This enables the combination of \textit{in situ} measurements with large-scale satellite measurements and increases the accuracy of hydrological models. Here, we show that BLOSM can measure this ratio under laboratory conditions.
- Due to the low-cost (<$1000) the detectors can be produced and deployed in large quantities. This in turn allows for an increase in data points and therefore gives a more accurate representation of the distribution of water on the land surface, once BLOSM can be deployed in the field.

Fig. 1. a) Schematic of the BLOSM setup. A dual-channel PCB is connected directly to the SiPMs in both detectors. This circuit filters, and amplifies the signal after which it can trigger on a pulse to output a digitised signal. Next, a Raspberry Pi receives the digitised signal, applies the Pulse Shape Discrimination (PSD) and outputs the counts and an estimate of the soil moisture content. b) Schematic of the inside of the detectors and the layered structure of the neutron sensitive ribbons.
• Real-time soil-moisture measurements give insight in the hydrological patterns and help us to predict forest fires, floods and droughts, as well as to optimise water use in agricultural areas.
• A single bare detector can be used as an economical thermal neutron detector. In the same way a single moderated detector can be used as an economical epithermal and fast neutron detector.

3. Design files summary

All files can be found in the online repository (https://osf.io/jgrm8/). There are three schematic files (pdf) that show how the different parts of the SiPM module, the ADC module, and the connection with the Raspberry Pi, are connected. These also show how these three parts should be connected. For each part, the Gerber files are provided, which can be used to have the different PCBs produced. The layouts of the PCBs are also provided as pdf. Finally, there are two Python scripts, one to be used on the Raspberry Pi to collect and store the data from the ADC, and one to be run off-line to analyse the data.

| Design filename                        | File type | Open source license | Location of the file |
|----------------------------------------|-----------|---------------------|----------------------|
| SiPM PCB layout                        | PDF       | CERN OHL V2         | OSF                  |
| SiPM PCB                               | Gerber files (.zip)* | CERN OHL V2         | OSF                  |
| SiPM module schematic                  | PDF       | CERN OHL V2         | OSF                  |
| Raspberry Pi (4) IOLe Adaptor Schematic| PDF       | CERN OHL V2         | OSF                  |
| Raspberry Pi (4) IOLe Adaptor PCB      | Gerber files (.zip) | CERN OHL V2         | OSF                  |
| ADC board schematic                    | PDF       | CERN OHL V2         | OSF                  |
| ADC board PCB                          | Gerber files (.zip) | CERN OHL V2         | OSF                  |
| Software ADC board                     | .hex      | CERN OHL V2         | OSF                  |
| Software Raspberry Pi serial read      | Python (.py) | CERN OHL V2         | OSF                  |
| Software Analyse Data                  | Python (.py) | CERN OHL V2         | OSF                  |

* The SiPM PCB Gerber files are derived from http://www.cosmicwatch.lns.mit.edu/Cosmic Watch muon detector.

4. Bill of materials summary

The quantities in the bill of materials are estimated for a setup consisting of two detectors with a sensitive area of 3100 cm². Each detector contains twelve fibers with a length of 2 meter. The fibers are placed at an interval of 7 mm and sandwiched by two scintillator ribbons of 8.4 cm × 184.5 cm.

| Component                                              | Number | Cost per unit | Total cost | Source of materials                  | Material type |
|--------------------------------------------------------|--------|---------------|------------|--------------------------------------|---------------|
| Kraton™D Polymers (SIS) D1161                          | 40g    | 40€/kg*       | 1.60€      | Kraton Polymers LLC                  | Polymer       |
| BN: HeBoFill LL-SP 010¹                               | 80g    | 364€/kg*      | 29.12€     | Ceratec Technical Ceramics BV        | Ceramic       |
| Zinc-sulfide silver-doped (ZnS:Ag) ²                  | 320g   | 450€/kg       | 144.00€    | WIN-TRUST Technology Co. LTD         | Inorganic     |
| White Spirit                                           | 0.5L   | 5€/L          | 2.50€      | Hardware store                       | Organic       |
| Poly-vinyl Alcohol (PVA)                               | 10mL   | 14€/L         | 0.14€      | Polyester shoppen                    | Polymer       |
| Mylar Reflective Foil                                 | 6200 cm² | 4.10/m²  | 2.54€      | Easygrow                              | Other         |
| Wavelength Shifting Fiber                             | 48m    | 5.50€/m*      | 264.00€    | Kuraray Y-11[300]                    | Polymer       |
| Oscilloscope¹                                          | 1      | 129€          | 129.00€    | Picoscope 2204A                      | Other         |
| Cable gland                                           | 4      | 1.09€         | 4.36€      | Skintop M12 Cable gland              | Other         |
| Counter Nut                                            | 2      | 1.52€         | 3.04€      | M12 counter nut                      | Other         |
| M3/M4 bolts (min. 50 mm)                              | 8      | 0.25€         | 2€         | Hardware Store                       | Other         |
| M3/M4 nuts                                             | 8      | 0.10€         | 0.80€      | Hardware Store                       | Other         |
| 3mm plywood (3 cm × 3 cm)                              | 4      | 1€            | 4€         | Hardware Store                       | Other         |
| Aluminium casing ø15cm                                 | 40cm   | 7€/m          | 2.8€       | Hardware Store orSpiroduct           | Other         |
| Aluminium lids ø15 cm                                  | 2      | 4€            | 8€         | Hardware Store orSpiro-lid           | Other         |
| HDPE tube (27.4 mm wall thickness)                      | 40 cm  | 150€/m*       | 60€        | RDM                                   | Other         |
Component Number | Cost per unit | Total cost | Source of materials | Material type
--- | --- | --- | --- | ---
HDPE sheet 2–3 cm (20 cm × 20 cm) | 2 | 40€ | 80€ | HDPE Sheet
Black isolation tape | 1 | 1€ | 1€ | Hardware Store
Optical Coupling Grease | 1 | 5€ | 5€ | iRad Silicone Coupling Compound

* : Inquiry based orders. Unit price is an indication and can differ due to lower or higher quantity order.
† : The oscilloscope can be replaced with any other ADC as long as it can compute one data point every 200ns for two channels.
‡ : To increase scintillation efficiency the particle size of the BN should be smaller than the ZnS:Ag particles to ensure that the ZnS:Ag is contained in a thin layer of BN. Here particles sizes of ~1 μm and ~7.5 μm are used for BN and ZnS:Ag respectively.

4.1. SiPM surface mount electronic parts

| Designator | Component | Number | Cost per unit – currency | Total cost – currency | Source of materials | Material type |
|--- | --- | --- | --- | --- | --- | --- |
| SiPM | SiPM (ON-semi MICROFC-60035-SMT-TR) | 2 | 22.45€ | 44.90€ | Mouser Electronics | Other |
| R1, R2, R3 | Resistance 49.9Ω 1% 1/8W 0805 | 6 | 0.09 | 0.54€ | Digikey | Other |
| C1, C2, C3, C4 | Capacitor CER 10000pF 50V X7R 0805 | 8 | 0.09 | 0.72€ | Digikey | Other |
| 6-pin | 6-pin Header | 2 | 0.61 | 1.21€ | Digikey | Other |

4.2. Bill-of-material custom PCB

The Bill of Materials of the ADC board and the Raspberry Pi adaptor can be found at OSF

5. Build instructions

5.1. Scintillator paint mixing

1.1 part Kraton D1161 is dissolved in 10 parts White Spirit by mass using a magnetic stirrer or by hand. The dissolving process might take a few hours and can be sped up by gently warming. Using a fume-hood or a well-ventilated area is necessary.
2.When the Kraton is completely dissolved, BN and ZnS:Ag powders are added, see Fig. 2a. The proportions used are 2:8:1 by mass BN:ZnS(Ag):Kraton (All mass proportions are 2BN: 8ZnS(Ag): 1Kraton: 10White Spirit). A stirrer or a spoon is recommended to roughly mix the powders with the Kraton mixture by hand, see Fig. 2b. More white spirit can be added to reduce the viscosity of the liquid as it will evaporate while drying later.
3.To achieve a more homogeneous mixture and increase scintillation efficiency, the mixture is mixed with a blender for 5 to 10 min until all visible lumps are removed and a homogeneous white mixture is achieved, see Fig. 2c.

5.2. Application of scintillator paint

4.For each detector two strips of Mylar of the desired dimensions are cut, see Fig. 3a. An extra margin is included for the tape, this is cut off in the final step. For a total surface area of 0.5m² approximately 1L of paint is needed.
5.The first layer is applied with a small paint roller with light pressure, see Fig. 3b. The first layer is applied in one go. Rolling the paint roller over wet paint causes the paint to be absorbed by the paint roller again.
6.The layer is dried before adding another layer in the same manner as in the previous step, see Fig. 3c. The direction of painting is changed each time to get a more homogeneous layer. This step is repeated until ten layers are applied. This will make a total layer thickness of roughly 250 um.
7. After the final layer of paint, two layers of poly-vinyl-alcohol (PVA) are applied at the painted surface with a paint brush, see Fig. 3d. This is to harden the surface of the paint so it will not be damaged by the fibers.

8. The surface of the final layer is not flat but textured. This poses no problem as long as the texture and thickness are roughly the same over the entire surface of the ribbon, see Fig. 3e.

9. When the PVA layers are dried, the margins where the ribbons were taped are cut off. The final result are ribbons with one layer of scintillator paint. The paint is flexible and will not crack when the ribbon is rolled up, see Fig. 3f.

5.3. Ribbon-fiber sandwich

10. The ribbons are glued with (spray) glue to a fabric. This fabric is used to prevent the mylar from tearing. The use of synthetic fabrics is discouraged due to the moderating effect it has on neutrons. Here a sheet of unbleached cotton is used. See Fig. 4a

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1 Initially, the PVA was applied to prevent alpha radiation created by Radon progeny in the air to reach the scintillator paint layer and create false neutron counts. However, the false neutron count contribution of the Radon progeny is small and will die out mostly within a few hours as the detector is nearly airtight and no new Radon-progeny will enter the detector. [13]
11. The ribbons are cut out with 1 cm margin on every side. The two parts are put on top of each other with the painted sides aligned and facing each other. See Fig. 4b.

12. At one side, the edge of the mylar is marked with a line, see Fig. 4c.

13. The two ribbons are sewn together along the marked line, see Fig. 4d.

14. The other lines are marked at the desired fiber interval, Fig. 4e.

15. A wavelength shifting fiber is placed along the sew line. Fig. 4f.

16. To guide the fiber, a thin tool (for example a screwdriver or a knife) is used. It is placed between the two ribbons just before the presser foot against the fiber such that it pushes the fiber to the left side of the presser foot, see Fig. 4g. The two previous steps are repeated until every fiber is fixed between the ribbons. Afterwards the margins are cut off. See Fig. 4h.

17. The final result is a flexible ribbon that keeps the fibers in place, Fig. 4i.

5.4. SiPM module

18. MDF or plywood is cut by a lasercutter in the shapes as seen in SiPM_module.pdf (3). It can also be done by hand with a handsaw and a drill except for the square window in the center of two of the pieces. This is where the SiPM is positioned and because of the tight fit it makes sure every fiber entering the window will connect to the SiPM.

19. Cable glands are fixed in the circular holes in the centers of the pieces, see Fig. 5a.

20. All fiber ends of a detector are put through the cable gland, see Fig. 5b. The cable gland is tightened well and the ends of the fiber are cut to make a rough plane of the fiber ends orthogonal to the direction of the fibers, Fig. 5c.

21. The plywood piece with the cable glands can be fixed in a vice to facilitate grinding of the fiber end interface. All ends of the fibers are ground with a file or a power-tool at once to achieve a rough flat plane interface, see Fig. 5d.

22. Afterwards, all fibers are polished to increase light collection through the fiber ends. This can be done by hand or by a power-tool. When using a power tool make sure a low RPM is used to prevent the fibers from melting, 5e. The fibers can be bundled with a tape to facilitate the polishing.
The result, Fig. 5f, is a flat interface of the polished fiber ends. The SiPM PCB is glued or taped (or both) to the other MDF piece of SiPM_module.pdf (3) with the square window such that the SiPM fits in the square window, Fig. 5g and h. Two shielded cables are soldered to the 6-pin header at the back of the SiPM module. One of the cable cores is attached to one of the left pins (HV), the core of the other cable is soldered to one of the right pins (SNG). Both grounds go to the center pins, see Fig. 5i.

A hole is drilled in the lids of the detectors to fit a cable gland. Both cables are put through the cable gland in the lid of the detector. The end of the cables on the other side of the lid are marked HV or SNG. The cable gland is tightened. Fig. 5i.

5.5. Casing installment

One end of the aluminium spiro tube is closed off with a spiro lid using a hammer. The HDPE tube is closed off as well with one of the HDPE sheets. The HDPE tube and sheet are glued or taped together. Black isolation tape is used afterwards to cover the seam to ensure it is light tight.

The ribbons are coiled or folded up and placed in their casings with the cable gland and the bundle of fibers at the top side. 6a

The two pieces of the SiPM module are attached to each other using four bolts and nuts (M4). The nuts are tightened but not forced which will cause damage to the SiPM. See also Fig. 6b.

The SiPM module is put inside the casing as well, making sure the fiber maximum bending diameter (10 cm) is not exceeded. 6c

The open ends of the casing are closed off with their matching lids the same way as in the first step. 6d

Each detector is connected to a channel on the oscilloscope or custom PCB. The HV cable is connected to a 29.5 V DC power source. This includes an overvoltage of 4.8 V to the SiPM and is used to increase the gain of the signal, a supplied...
voltage higher than 30 V may cause damage to the SiPM. The SNG cable is connected to the channel of the oscilloscope or the custom PCB, see Fig. 6f.

6. Operation instructions

6.1. Data acquisition

The Picoscope or the custom ADC is connected to the SiPM. A custom-made PCB is preferred to be able to filter and amplify the signal and increase the resolution. Shielded cables are recommended to reduce electromagnetic noise in the signal. The unamplified baseline of the signal should range between $-2 \text{ mV}$ to $+2 \text{ mV}$ if the casing is light-tight. Then a trigger can be set at $6 \text{ mV}$ above the baseline value in the unamplified signal. A pulse with a width smaller than $20 \text{ ns}$ can be ignored, every other pulse has to be distinguished as either neutron or gamma/noise (6.2) directly or be saved and analysed later.

6.2. Pulse shape discrimination

The ZnS:Ag has been used as a scintillator since the first half of the 20th century because of its scintillation efficiency and its scintillation decay characteristics [7]. However, the opaqueness of ZnS:Ag demands thin layers in order for the scintillation to be visible at the surface. This, in turn, provides an insensitivity to $\gamma$-rays because the small thickness of the layers of scintillating material prevent most $\gamma$-rays from depositing a large enough portion of their energy to be detected. Still there are scintillation pulses that can be assigned to gamma’s which have to be recognised and rejected.

Fortunately, the scintillation decay of a $\gamma$-ray excitation is short, 0.1 ns to 10 ns, while the scintillation decay of an $\alpha$-particle (emitted after neutron absorption by $^{10}\text{B}$) is longer, up to 10$\mu$s [3]. This property opens up a robust way to discriminate between particles using these pulse shapes. An often used method is to define a parameter calculating the fraction of the charge in the tail of the pulse with the charge of the total pulse [9]. The $P$-parameter is defined as,

$$P = \frac{Q_{\text{long}} - Q_{\text{short}}}{Q_{\text{long}}}$$

with $Q_{\text{long}}$ and $Q_{\text{short}}$ the integrated signal of the long part and short part of the signal, respectively. The time gates are set at $t_{\text{short}} = 400 \text{ ns}$ and $t_{\text{long}} = 4000 \text{ ns}$ but can be tweaked for better peak separation ($t = 0$ corresponds to the trigger).

Due to the decay characteristics of ZnS:Ag, $\gamma$-ray pulses will be indicated by low $P$ values while neutrons (i.e. $\alpha$-particles) are indicated by higher values of $P$. For every pulse, the $P$-parameter is determined. Afterwards, a histogram for all pulses categorised by values of the $P$-parameter is made. After a sufficient number of counts, two clear peaks will be visible in the histogram. The minimum value between the two peaks is the PSD threshold. This step has to be done only once when

![Fig. 6. Casing installment.](image)
installing a setup and can be ignored in later runs when the PSD threshold is already determined. Neutrons are counted by
counting pulses for which $P > \text{PSD threshold}$.

To determine if the pulse shape discrimination is efficient in distinguishing neutrons from gamma’s a Figure-of-Merit can
be calculated [15]. The Figure-of-Merit (FoM) is defined as:

$$\text{FoM} = \frac{\langle n \rangle - \langle \gamma \rangle}{\text{FWHM}_n + \text{FWHM}_{\gamma}}$$

Here, $\langle n \rangle$, $\langle \gamma \rangle$ and $\text{FWHM}_n$, $\text{FWHM}_{\gamma}$ indicate the centroids and full-widths-at-half-maximum of the peaks (or their Gaussian
fits), respectively. A FOM value greater than 1.27 is used as a reference parameter to define efficient PSD [20].

6.3. Operation

There are different ways of putting the Python scripts on the Raspberry Pi such as with a SD card or through WiFi. We
used WiFi and TeamViewer software (teamviewer.com) to connect from any PC to the Raspberry Pi. The BLOSM_raspi.py
is run using, in our case, the Thonny Python IDE (thonny.org). The script will run until stopped.

After a trigger from the ADC, the python script running on the Raspberry Pi (BLOSM_raspi.py) will convert the bytes from
the ADC to a string of numbers. It will save the channel, the timestamp (unix), and the entire string of numbers to memory. It
will repeat this until it has saved 256 pulses. Then it will save all data in memory to a.csv file, after which it starts to collect
pulses again.

All.csv files are zipped and transferred to a PC that runs the analysis script (BLOSM_analyse.py). Running this script will
read all.csv files in the directory and turn it into a histogram of both detectors. We did not want to do much processing on the
Raspberry Pi, which is why the preference was to download the complete pulse shapes and perform the analysis off-line. This
also allows tweaking of the processing parameters.

7. Validation and characterization

The response of both detectors to thermal and fast neutrons is shown in Fig. 8. The first part of the experiment took place
in a tube with Cadmium plating of the Reactor Institute Delft, see Fig. 7, to lower the amount of thermal background neu-
trons and highlight the effect of the neutron source. A significant drop in neutron counts can be seen after the shutdown of
the reactor on Jan-29 22:00. The principal part of neutrons emitted by the reactor have thermal energies which are blocked
by the Cadmium plating on the tube and cause the lower count rate of the bare detector in comparison with the moderated
detector.

The response to thermal neutrons is visible in both detectors. The count rate of the moderated detector is 60% of the count
rate of the bare detector for thermal neutrons, with background subtracted. This part of the thermal neutrons is able to pen-
etrate through the HDPE moderator and enter the detector. A solution to this is to surround the HDPE moderator with a piece
of thermal neutron shielding material, like boron rubber, to block thermal neutrons and allowing only fast neutrons to be
thermalized and reach the detector. This will be part of future design and research.

The response to fast neutrons is also visible in both detectors, although the bare detector response is only 7% in compar-
ison to the moderated detector response, which shows the effectiveness of the moderator. The minimal response of the bare
detector is caused by the neutron cross-section of $^{10}\text{B}$ which is small for fast neutrons but still sufficient to absorb a few
neutrons.

Under atmospheric background conditions (Delft, the Netherlands), the count-rate of the bare detector ($\sim 6000$ per day $\pm$
1.3%) is slightly higher than the moderated detector ($\sim 4800$ per day $\pm$ 1.4%).

The Figures-of-Merit (FoM) can also be seen in Fig. 8 on the right side. The peaks indicating $\gamma$-rays (left) and neutrons
(right) can be easily distinguished which is also reflected by the FoM values being greater than 1.27.

![Fig. 7. Setup BLOSM in Cadmium tube at the Reactor Institute Delft.](image-url)
In conclusion, the count rate of both detectors is high enough to get a daily count with an error smaller than 1.5% and Pulse Shape Discrimination can be carried out accurately. The moderated detector is able to detect fast neutrons efficiently while it is also sensitive to thermal neutrons. The bare detector can be used to determine the part of the neutron spectrum with thermal energies.

The mean coefficient of variation is approximately 1.3% for a daily measurement with a count of 6000 neutrons (mean daily atmospheric neutron count for the described setup). The coefficient can vary depending on the count-rate, i.e. the size of the neutron sensitive material, the scintillation efficiency and atmospheric neutron production.

With a custom PCB + Raspberry Pi setup, the power consumption varies between 4 W and 6 W which can easily be provided by a solar panel to create a standalone setup. If a laptop and Picoscope are used for data acquisition, the power consumption can increase to 60 W to 100 W per detector which makes this setup only suitable for labs or places with a power outlet.

The setup is made to be constantly operating to monitor the neutron count for long time-spans. The neutron-sensitive material will be affected little by environmental conditions because of the air-tight and light-tight casings. Only temperature changes will influence the electronics, the SiPM will experience more thermal noise peaks at higher temperatures which should be rejected after PSD if done correctly.

7.1. Further work

It should be stressed that we present here only the laboratory validation of the detectors that shows that we can indeed detect and count thermal and fast neutrons. There is still work do be done before this set-up has been tested in the field. In principle, we can measure the ratio between thermal and fast neutrons, which should give an estimation of the soil-moisture content when other neutron-moderating factors in the environment are neglected. These factors, for instance water vapour, vegetation and surface water can be accounted for with corrections which have to be calibrated. Several soil samples have to be taken from the area to determine the initial soil-moisture factor. To correct for water vapour and air pressure each detector should be equipped with a hygrometer and a barometer. The correction factors are well documented in earlier research and their magnitude can be easily determined with known equipment [22]. Given that CRNS has been extensively proven to correlate with large scale soil moisture, not a complete method validation would be needed but some field campaigns that include traditional soil moisture measurements, will be needed to show that the intended use of BLOSM is feasible in the field.

CRediT authorship contribution statement

Edward Amelrooij: Methodology, Validation, Formal-analysis, Investigation, Data-curation, Writing-original-draft, Visualization. Nick de Giesen: Conceptualization, Writing-review-editing, Supervision, Project-administration, Funding-
acquisition. **Jeroen Plomp**: Conceptualization, Investigation, Resources, Writing-review-editing. **Michel Thijs**: Investigation, Resources, Writing-review-editing. **Tomáš Fico**: Methodology, Software, Resources.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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We have used the PCB designs from the Cosmic Watch Muon Detector as an example for our first prototypes. It has provided us with an easy way to power and readout the SiPM for which we are thankful. Even if you are not interested in muon detection the project is worth looking into.

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