Peer Review File

Verification of the Outer Space Treaty with Cosmic Protons

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This file contains all reviewer reports in order by version, followed by all author rebuttals in order by version.

Version 0:

Reviewer comments:

Referee #1

(Remarks to the Author)
The author in this manuscript proposes a passive verification concept for potential outer space treaty violations by detecting spallation neutrons produced when ~GeV trapped protons interact with the special nuclear high-Z material (assumed uranium in this case) in a space-based thermonuclear device. This is a well-written and high-impact concept feasibility paper. In my opinion, this work is of interest to the nonproliferation community and explores an important area that has not received proper attention yet. It deserves publication provided the author improves the manuscript by strengthening uncertainty treatment, quantifies false alarm risk, and provides additional quantitative evidence for detection claims.

Key results: This manuscript provides a clear physics-based signature by leveraging naturally present >200 MeV trapped protons to induce neutron production (no active interrogation).

The concept of a 9U CubeSat detector architecture is plausible and the detector design is novel and includes veto layers for background and charged-particle rejection.

Originality: The concept is original as it proposes a new passive method using trapped-belt protons as an interrogation field.

Data & methodology: The overall approach (spallation source estimate, Geant4 pixel response and directional reconstruction, time-to-detection scaling) is reasonable for a feasibility study.
The manuscript indicates AP9/AE9 (IRENE) model usage and Geant4 simulations. A GitHub repository includes scripts and data for key figures and calculations. However, some quantitative steps are not described at a level that may fully enable independent reproduction without the repository (e.g., exact energy binning, geometric cross-sectional assumptions, full neutron energy spectrum used, etc.).

Appropriate use of statistics and treatment of uncertainties: The detection estimate uses a Poisson counting argument with a mean count threshold (e.g., setting c=5 to achieve ~99% probability of ≥1 count). This is mathematically consistent for a simple “at least one event” criterion, but it is not the standard hypothesis-testing framework for detection in background (false-alarm probability is missing). Because the method heavily relies on background rejection, the paper should include an explicit false positive / false negative discussion.

Efficiency is quoted with an uncertainty but it is unclear how this was computed (MC statistics only? systematic effects?).

The feasibility of the required standoff distance and observation time at ~4 km in ~7 days is not discussed in detail neither supported by an orbital analysis.

The statistical treatment is acceptable for a first-order feasibility estimate but the largest uncertainty, the spallation source term and shielding dependence, is not discussed nor quantified.

Conclusions: The conclusion that passive detection using trapped protons and directional neutron sensing is well supported by the modeling narrative and MC demonstrations of charged-particle rejection and directional discrimination.

However, the conclusion 4 km in ~1 week with 9U CubeSat is not completely robust because it depends strongly on assumed weapon composition and geometry and unmodeled shielding and uncertainties in the spallation yield.

Suggested improvements: To strengthen the work substantially, I suggest:
Perform sensitivity and uncertainty analysis of the source term.

Vary uranium mass, geometry, and evaluate plausible shielding thickness and show impact on Y, signature degradation, and time-to-detect. Even though the manuscript itself flags this as future work, incorporating even one bounding case would significantly improve credibility.

Considering the implications of false alarms, please compute detection significance with a defined false-alarm probability.

Add a short orbital mechanics assessment demonstrating that the “inspector below suspect during peak proton flux” condition is maintainable and reasonable.

Referee #2

(Remarks to the Author)
This paper presents a proposed methodology for confirmatory verification of nuclear weapons in space by detecting proton-induced spallation neutrons generated within the warhead.

The author examines potential sources of background and noise, and the concept appears theoretically feasible. While rejecting charged particles should be straightforward with the proposed methodology, the neutron background can potentially reduce the specificity of the method.

Using the stated source strength and assuming a representative LEO neutron background of
0.1 n cm^−2 s^−1, I estimated the probability of an accidental coincidence and found it to be negligibly small compared with the expected rate of true coincidences, i.e., coincidences due to a detection and scattering event in the top plane of detectors also detected by the bottom layer.
This supports the feasibility of the proposed a-posteriori localization approach, i.e., verifying the origin of the neutrons after detection.

The key remaining issue is whether the method can reliably discriminate fissile material from alternative high-Z materials (e.g., lead or tungsten) that may also produce substantial proton-induced spallation neutrons.

It would strengthen the discussion to present reconstructed images using (i) all recorded events and (ii) only accepted events, and then compare the two to illustrate the impact of the event-selection criteria on image quality and localization performance.

Minor comments on the cited neutron scatter cameras: the referenced systems are either simulation-based studies or comparatively large instruments that may not directly scale to the dimensions of the proposed setup.
In Section "dead layer of 60 nmA" should be "dead layer of 60 nm".
Section 3.2 would benefit from clarifying the intended units for the organic scintillator signal. In practice, the calibrated light-output is typically reported in electron-equivalent units (keVee or MeVee); neutron energy can then be inferred by applying the detector’s quenching (light-output) response.

Version 1:

Reviewer comments:

Referee #2

(Remarks to the Author)

Referee #3

(Remarks to the Author)
My comments were addressed, thanks.
Angela Di Fulvio

The author would like to thank the reviewers for their thoughtful and constructive comments and suggestions.
The reviewer comments are in **black**.
Responses are in **blue**.

Referee #2 (Remarks to the Author):

The author in this manuscript proposes a passive verification concept for potential outer space treaty violations by detecting spallation neutrons produced when ~GeV trapped protons interact with the special nuclear high-Z material (assumed uranium in this case) in a space-based thermonuclear device. This is a well-written and high-impact concept feasibility paper. In my opinion, this work is of interest to the nonproliferation community and explores an important area that has not received proper attention yet. It deserves publication provided the author improves the manuscript by strengthening uncertainty treatment, quantifies false alarm risk, and provides additional quantitative evidence for detection claims.

Key results: This manuscript provides a clear physics-based signature by leveraging naturally present >200 MeV trapped protons to induce neutron production (no active interrogation).

The concept of a 9U CubeSat detector architecture is plausible and the detector design is novel and includes veto layers for background and charged-particle rejection.
Thank you.

Originality: The concept is original as it proposes a new passive method using trapped-belt protons as an interrogation field.
Thank you.

Data & methodology: The overall approach (spallation source estimate, Geant4 pixel response and directional reconstruction, time-to-detection scaling) is reasonable for a feasibility study. The manuscript indicates AP9/AE9 (IRENE) model usage and Geant4 simulations. A GitHub repository includes scripts and data for key figures and calculations. However, some quantitative steps are not described at a level that may fully enable independent reproduction without the repository (e.g., exact energy binning, geometric cross-sectional assumptions, full neutron energy spectrum used, etc.).
As the reviewer noted, this information is embedded in the various analysis scripts and Jupyter notebooks in the GitHub repository. To make it more explicit, the axes of the histograms in Fig. 3 have been modified to clearly state the bin sizes. The neutron spectrum, as described in Fig. 3 of the paper by Carpenter[1] , is included in the GitHub repository; the Appendix now has been modified to include a direct url link to the text file which describes the spallation neutron spectrum for uranium. By “geometric cross-sectional assumptions” I assume the reviewer means that of the inspecting satellite. The geometric parameters of the 9U detection system are described in a number of places in the manuscript, e.g. Section 3.3: “In this system, the two detection planes are 30 X 30 arrays of 1~cm pixels, as described earlier, separated by a distance of 10~cm. This amounts to the size of a 9U CubeSat.”

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[1] Carpenter, J.M.: Pulsed spallation neutron sources for slow neutron scattering. Nuclear Instruments and Methods 145(1), 91–113 (1977)

Appropriate use of statistics and treatment of uncertainties: The detection estimate uses a Poisson counting argument with a mean count threshold (e.g., setting c=5 to achieve ~99% probability of ≥1 count). This is mathematically consistent for a simple "at least one event" criterion, but it is not the standard hypothesis-testing framework for detection in background (false-alarm probability is missing). Because the method heavily relies on background rejection, the paper should include an explicit false positive / false negative discussion.
During the analysis it was determined that the false positive rate is negligibly small, due to efficient rejection of charged particles and atmospheric albedo neutrons.

However the reviewer is completely right: given the nature of the detection problem this needs to be demonstrated explicitly and communicated clearly. An additional extensive simulation has been run for the expected false positive due to the mixing between atmospheric and spallation neutrons, and an upper limit on the FP rate has been determined to be <1%. Due to limitations on word count, a section has been added to the Supplementary Information document explaining how the false positive rate is calculated: see "Supplementary Information: False Positive Rate". It is also referred to in the main body, in Section 3.3 and 4.4.

Efficiency is quoted with an uncertainty but it is unclear how this was computed (MC statistics only? systematic effects?).
Agreed. The text has been amended to explicitly state the source of uncertainty in efficiency (MC statistics).

The feasibility of the required standoff distance and observation time at ~4 km in ~7 days is not discussed in detail neither supported by an orbital analysis.
Appendix A in manuscript lists specific instances of Russian, US, and Chinese satellite flybys. In particular in 2022 Russian satellite Luch Olymp flew by US Intelsat 37E at the distance of just 4 km.

However the reviewer is correct in noting that these are examples of single flybys, and that the manuscript doesn't include any clear examples of ~7 day proximity operation between chief and a deputy satellites. There are however many such examples, see the PROBA-3 mission where the inter-satellite distance was just 150 m. To reflect this, the Appendix has been amended to include a reference to PROBA-3 to further strengthen the argument for the technical feasibility of 4 km observation distance. Additionally, Supplementary Note 0 now describes an orbital analysis showing the feasibility of a 4 km standoff.

The statistical treatment is acceptable for a first-order feasibility estimate but the largest uncertainty, the spallation source term and shielding dependence, is not discussed nor quantified.
The spallation source term is based on an empirical model for neutron spallation by protons, derived by Carpenter. The model is based on experimental data and assumes 95 kg of uranium. It is a "go to" first order model used in the field. That said, I agree that this point needs to be made more clear in the manuscript. The text has been amended to make this more clear.
For shielding considerations – see below.

Conclusions: The conclusion that passive detection using trapped protons and directional neutron sensing is well supported by the modeling narrative and MC demonstrations of charged-particle rejection and directional discrimination.
Thank you.

However, the conclusion 4 km in ~1 week with 9U CubeSat is not completely robust because it depends strongly on assumed weapon composition and geometry and unmodeled shielding and uncertainties in the spallation yield.
The reviewer is absolutely correct to point out that the weapon composition significantly affects the spallation neutron source term.
The empirical model published by Carpenter and used in this study has been based on experimental data involving 95 kg of uranium, and the uranium mass is not a variable in this model. This makes it difficult to determine neutron source terms for different masses based on this model alone; this should be left to future, classified research. That said, it can be argued that the estimate from the Carpenter model is a *lower limit* to the neutron source term, for the reasons listed below.

It is impossible to make any exact assumptions about thermonuclear weapon composition, as most design information is classified and publicly inaccessible. There is however some public information about the US designs that indicates that the mass of the fissionable material on a W87 warhead could be 200 kg (see Ref. [1] in SI). According to declarations in the framework of the START treaty the Russian R-36 missile has a throw-weight of 8800 kg and 10 multiple reentry vehicles (MIRV), making the weight of one Russian MIRV 880 kg (See Ref [2] in SI). This analysis implies Russian weapon masses that could be multiple times larger than that of W87, assuming that most of the weight of the weapon is in its fissile material. This study assumes only 95 kg, as it is the basis of the Carpenter model used in this study. It is thus reasonable to use the Carpenter model as a basis for neutron spallation as a *lower limit* for the neutron source term.

Ultimately the final goal of this study is not to show a definitive answer as to whether the technique is feasible, but rather to build an analysis framework that can be used by specialists with access to classified information to perform more detailed simulations and calculations and thus determine the performance of the proposed approach.
The text in the manuscript has been amended to make these considerations clear. I added a brief section in Supplementary Information (Supplementary Note 1) to account for the above and referenced it in Section 2. A mention of the uncertainties of the weapon composition has been added to the Conclusion.

Suggested improvements:

To strengthen the work substantially, I suggest:

Perform sensitivity and uncertainty analysis of the source term.
See the responses above.

Vary uranium mass, geometry, and evaluate plausible shielding thickness and show impact on Y, signature degradation, and time-to-detect. Even though the manuscript itself flags this as future work, incorporating even one bounding case would significantly improve credibility.
For the uranium mass uncertainty and weapon design – see the response above. Understanding what shielding types are possible for a weapon placed in the outer space environment is not a simple task, which is why it has been delegated to future research efforts. While in ground-based systems neutron shielding is trivial, in outer space it is a much more complex problem. The neutron shielding will act as thermal insulation, which will make it more difficult to remove the ~10 W of alpha heating and any additional heating due to the increase in fission triggered by protons. Given that the weapon is expected to serve for years, any accumulation of heat due to the additional insulation may result in an increase in the weapon component temperatures, possibly affecting their reliability in the case of nuclear use.

Nevertheless, to address the reviewer suggestion, I have run additional MC-based calculations for 5-20 cm of polyethylene shielding scenarios, showing how the required size of the inspector satellite changes from 9U to greater values to achieve the same level of detection in 7 days. For the 20 cm shielding scenario the detector size will need to be expanded from 0.3 x 0.3 m^2 to 1.6 x 1.7 m^2. This short analysis has been described in the Supplementary Note 2 and has been referenced in the main body.

Considering the implications of false alarms, please compute detection significance with a defined false-alarm probability.
See the response above. The false alarm rate has now been explicitly studied, and the results are presented in the Supplementary Information and referenced in the main body.

Add a short orbital mechanics assessment demonstrating that the “inspector below suspect during peak proton flux” condition is maintainable and reasonable.
Agreed. A section has been added to Supplementary Information (see Supplementary Note 0) describing a relative motion between the chief (kosmos 2553) and a deputy (inspector) with a +-4km radial oscillatory offset. A close-proximity inspection scenario was modeled using the linearized Clohessy-Wiltshire equations about an approximately circular reference orbit. This model shows that it is feasible to achieve an orbit with inspection positioning with a radial offset of -4 km.

Referee #3 (Remarks to the Author):

This paper presents a proposed methodology for confirmatory verification of nuclear weapons in space by detecting proton-induced spallation neutrons generated within the warhead.

The author examines potential sources of background and noise, and the concept appears theoretically feasible. While rejecting charged particles should be straightforward with the proposed methodology, the neutron background can potentially reduce the specificity of the method.

Using the stated source strength and assuming a representative LEO neutron background of 0.1 n cm^−2 s^−1, I estimated the probability of an accidental coincidence and found it to be negligibly small compared with the expected rate of true coincidences, i.e., coincidences due to a detection and scattering event in the top plane of detectors also detected by the bottom layer. This supports the feasibility of the proposed a-posteriori localization approach, i.e., verifying the origin of the neutrons after detection.
Thank you for this analysis.

The key remaining issue is whether the method can reliably discriminate fissile material from alternative high-Z materials (e.g., lead or tungsten) that may also produce substantial proton-induced spallation neutrons.
The reviewer is correct to point out that non-fissionable high-Z materials, such as lead or tungsten, do generate some spallation neutrons. However the purpose of the technique is to differentiate between common civilian satellites and one that carries a weapon. Civilian satellites are primarily built from low-Z elements, such as aluminium and hydrogenous materials, which generate negligible rates of spallation. While a satellite causing an alarm could theoretically contain ~200 kg of lead, that would be most unusual and highly suspicious in of itself.

I do agree that this is an important point that should be addressed in the manuscript. A paragraph has been added at the end of Section 4.4 to clarify this important circumstance.

It would strengthen the discussion to present reconstructed images using (i) all recorded events and (ii) only accepted events, and then compare the two to illustrate the impact of the event-selection criteria on image quality and localization performance.
The approach presented in the manuscript, rather than relying on images per se, applies anti-coincidences to reject charged and directional reconstruction via inter-plane coincidences and TOF to reject Earth's albedo neutrons. See Fig 3: (a) shows the rejection of the protons, while (b) shows the rejection of the albedo neutrons. Only the events right of the blue threshold line in Fig. 3(b) are accepted; the rest are rejected.

I now realize that the explanation in the caption of Fig 3 may have been not sufficiently clear. It has been modified to better explain this important point. The caption now clarifies that all albedo neutrons and protons are rejected, while 87% of counts from spallation neutrons are retained.

Minor comments on the cited neutron scatter cameras: the referenced systems are either simulation-based studies or comparatively large instruments that may not directly scale to the dimensions of the proposed setup.
Agreed. A citation has been added to a recent work by Keefe et al. describing a series of characterization measurements on an experimental compact neutron scatter camera.

In Section "dead layer of 60 nmA" should be "dead layer of 60 nm".
Thank you. Fixed.

Section 3.2 would benefit from clarifying the intended units for the organic scintillator signal. In practice, the calibrated light-output is typically reported in electron-equivalent units (keVee or MeVee); neutron energy can then be inferred by applying the detector’s quenching (light-output) response.
Agreed. Clarifying text has been added.

Additional changes:

1. Minor wording edits for clarification
2. Fig 3(b) has been changed to include higher statistics MC run outputs for albedo neutrons. Additionally, the vertical blue line has been replaced with a blue shaded region, to be stylistically consistent with Fig 3(a)
3. The Acknowledgements section has been expanded to express gratitude to a broader set of scholars and scientists for their contributions.