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Space Weather Research and Ionizing Radiation Monitoring in Support of Space Domain Awareness within the Czech Armed Forces

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Abstract

This study proposes a time-synchronised airborne–ground semiconductor radiation measurement architecture for in-situ validation of space weather models in military aviation environments. The work defines a measurement research proposal using a JAS-39 Gripen platform equipped with a semiconductor detector and a ground-based reference system, rather than reporting results. The framework enables correlation of radiation measurements with space weather datasets, operational forecasts, and the AVIDOS dosimetric model for aviation radiation exposure. It supports model validation and improves characterisation of the aviation radiation environment. Overall, the research proposal enhances Space Domain Awareness by increasing availability of in-situ radiation data in flight conditions.

KEY WORDS: *space weather, aviation radiation, semiconductor detector, galactic cosmic rays, solar energetic particles, single event effects, JAS-39 Gripen, Space Domain Awareness*

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1. Introduction

Space weather (SWx) represents a critical environmental factor influencing reliability, safety, and operational effectiveness of modern military systems. Although driven primarily by solar activity, its disruptive impacts have only been systematically recognised and studied in modern scientific and operational frameworks and are most pronounced in technologically advanced infrastructures [1]. Within the framework of Space Domain Awareness (SDA), SWx constitutes a key environmental domain, while Space Situational Awareness (SSA) provides the capability for its monitoring and analysis [2].

NATO armed forces increasingly depend on Global Navigation Satellite Systems (GNSS), satellite communications, and data-driven command-and-control systems, which significantly increases their vulnerability to SWx phenomena. These phenomena may result in GNSS signal degradation, communication disruptions, and elevated radiation exposure affecting both systems and personnel [3].

Despite its operational relevance, a major limitation remains the insufficient availability of in-situ observations for validating SWx models, resulting in a persistent gap between modelled and observed conditions [1]. To address this limitation, this paper proposes a structured experimental research proposal for in-situ measurements of ionising radiation in military aviation. The study is deliberately limited to a conceptual and architectural design without presenting operational measurement data. The primary objective is to establish a time-synchronised airborne–ground measurement framework enabling systematic comparison of in-situ radiation data with SWx observations, operational forecasts, and radiation models. The main contribution of this work is the design of an integrated measurement research proposal that enables model validation and improves the operational applicability of SWx information within the SDA framework.

In addition, the study supports the development of operationally relevant radiation monitoring capabilities in alignment with the NATO Military Space Weather Technical Panel (Programme of Work 15 – Radiation Sensors) to enhance Allied understanding of the atmospheric ionising radiation environment, improve modelling and forecasting of radiation effects on aviation systems, and contribute to operational advantage.

2. Space Weather in SDA Context

Within the NATO SDA framework, SWx is an environmental factor affecting the performance and reliability of space- and ground-based systems, and in certain contexts, human health. According to NATO STO Technical Report TR-SCI-229, *Space Environment Support to NATO Space Situational Awareness*, SWx must be continuously observed, modelled, and forecasted to support operational awareness and mission planning, while SSA provides the capability to monitor, analyse, and assess space environment conditions and their impacts on space- and ground-based systems [2].

The NATO Standardization Office defines SWx as *"the variable conditions in interplanetary space, usually caused by solar phenomena, which may affect human health and/or technological systems"* [4]. These conditions are primarily associated with solar flares, coronal mass ejections (CMEs), and solar energetic particle (SEP) events interacting with the Earth's magnetosphere and ionosphere [3]. Such phenomena can result in radio blackouts, geomagnetic storms, and solar radiation storms, which are classified on the NOAA Space Weather Scale from 1 (minor) to 5 (extreme) [5]. In operational environments, multiple effects may occur simultaneously, increasing overall system vulnerability [6].

From an operational perspective, SWx can degrade GNSS performance, disrupt satellite communications, and affect onboard avionics systems. The increasing reliance on GNSS-based positioning, navigation, and timing (PNT) services further amplifies system vulnerability, particularly in autonomous and network-centric military operations [11]. This dependence highlights the need for SWx-aware and resilient navigation concepts [12]. Historical observations confirm that extreme SWx events have caused operational impacts across military and civil domains, affecting communication, radar performance, and navigation reliability [7–10].

Despite significant progress in SWx modelling and forecasting provided by organisations such as NOAA SWPC, ESA SSA, and ICAO, current systems rely primarily on space-based sensors and ground observatories. This results in limited spatial and temporal resolution of radiation measurements in the near-Earth environment, particularly at aviation flight levels [13]. This limitation represents a key gap in SDA capability: the lack of direct, time-synchronised in-situ radiation data from operational airborne platforms.

To address this gap, this study proposes a measurement research proposal based on airborne and ground-based semiconductor detector systems. The objective is to establish a framework for collecting radiation data in operational flight conditions and correlating them with SWx observations and forecast models. This approach is intended to support improved model validation, enhance environmental awareness within SDA, and strengthen the empirical basis for assessing radiation effects on both systems and aviation operations.

In this context, the expansion of in-situ measurement capabilities is increasingly recognised as a relevant development pathway. Operational platforms such as commercial aircraft represent a potentially scalable and cost-effective means of increasing observational density in near-Earth space environments. Such approaches may contribute to improved data availability, enhanced model validation, and increased operational resilience of space-dependent systems, including those relevant to NATO.

3. Ionizing Radiation in the Aviation Environment

This section summarises the key characteristics of the aviation radiation environment relevant for the design and interpretation of the proposed measurement architecture.

Aviation operations are significantly influenced by SWx, with increasing flight altitude leading to higher exposure to ionising radiation due to reduced atmospheric shielding. This effect is further amplified at polar latitudes, where geomagnetic shielding is weaker and the access of high-energy particles to the atmosphere is enhanced [14]. In addition, to human exposure, ionising radiation can also affect avionics systems through Single Event Effects (SEE), making radiation monitoring relevant for both personnel safety and system reliability [3].

From a measurement perspective, the aviation radiation environment is characterized by strong spatial and temporal variability, driven by solar activity and geomagnetic conditions. This variability limits the accuracy of global models when used without direct observational constraints, particularly at aviation flight levels. As a result, in-situ measurements are required to improve model fidelity and operational applicability.

To address this limitation, the proposed study introduces a time-synchronised airborne–ground measurement research proposal enabling correlated observations of the radiation field in operational flight conditions. This approach provides the necessary observational basis for validating SWx and dosimetric models under realistic atmospheric exposure scenarios.

The operational relevance of SWx in aviation is recognised in ICAO Doc 10100, *Manual on Space Weather Information for International Air Navigation*, which defines requirements for SWx information in supporting international air navigation [15]. However, current operational frameworks rely primarily on space-based sensors and ground observatories, which provide limited resolution in the atmospheric flight domain, thereby highlighting the need for complementary in-situ airborne measurements.

3.1 Sources of Radiation in Aviation

Ionising radiation at flight altitudes originates from cosmic radiation, primarily from cosmic radiation, consisting of galactic cosmic rays (GCR) and SEP [16]. GCR provide a continuous background of high-energy particles originating outside the Solar System, composed mainly of protons and helium nuclei with a minor contribution of heavy ions [18].

SEP events are transient phenomena associated with solar flares and coronal mass ejections, typically proton-dominated but occasionally including heavier ions and electrons [17].

These primary particles interact with the Earth's atmosphere, producing secondary particle cascades composed of neutrons, protons, electrons, muons, and gamma radiation. At typical aviation altitudes, secondary neutrons dominate the radiation field in terms of effective dose contribution [17].

From a measurement perspective, this mixed and dynamic radiation field represents the primary observable quantity for airborne detection systems. However, due to its dependence on altitude, latitude, and solar activity, reliable characterisation requires time-synchronised measurements from both airborne and ground-based detectors, enabling separation of spatial and temporal variability effects from instrumental or model uncertainties.

In rare cases, ground level enhancements (GLEs) can occur, producing measurable increases in secondary particle fluxes at both ground level and aviation altitudes [19, 20]. These events are particularly relevant for validating SWx models due to their clear temporal signatures and broad spatial footprint.

3.2 Impact on Flight Crew

Radiation exposure of aircrew is quantified using effective dose, which accounts for radiation type and biological effectiveness. Depending on flight hours and routes, annual doses may reach several millisieverts [21]. According to Council Directive 2013/59/Euratom, the dose limit is 1 mSv per year for the general public and 20 mSv per year (averaged over five years) for occupationally exposed aircrew. In operational practice, a reference level of 6 mSv per year is used for exposure monitoring and control [22].

The primary health risk is stochastic in nature, mainly associated with long-term cancer induction, with probability increasing approximately linearly with cumulative dose. Although absolute risk at aviation exposure levels remains low, it becomes operationally relevant for long-duration and high-latitude flight profiles [21].

From a modelling perspective, dose estimation tools such as AVIDOS are used to predict radiation exposure along flight trajectories. However, these models rely on parameterised representations of the radiation environment and require empirical validation. The proposed airborne–ground measurement architecture enables direct comparison between modelled dose rates and in-situ measured radiation fields, improving the reliability and operational validity of such dosimetric models under real flight conditions.

3.3 Impact on Electronics (Single Event Effects)

High-energy particles in the aviation environment can induce SEE in semiconductor devices through localized energy deposition [17]. These effects represent a key link between SWx variability and avionics system reliability.

The radiation environment responsible for SEE is composed of a dynamic mixture of GCR, SEP, and atmospheric secondary particles. Accurate prediction of SEE rates therefore requires integrated environmental modelling rather than isolated source assumptions [17]. However, such models remain sensitive to uncertainties in the underlying particle spectra and atmospheric transport processes.

At aviation altitudes, secondary neutrons are the dominant contributors to SEE, primarily through nuclear interactions within semiconductor materials, producing secondary charged particles that deposit energy in sensitive device volumes. These secondary particles deposit energy in sensitive device volumes and can induce single event upsets, i.e., transient bit flips. Protons and heavy ions also contribute, particularly through direct ionisation processes [17].

SEE are classified as [23]:

- SEU (Single Event Upset): transient bit flip
- SEL (Single Event Latch-up): potentially destructive high-current state
- SET (Single Event Transient): temporary signal disturbance
- SEB (Single Event Burnout): catastrophic failure in power devices

Modern avionics systems mitigate SEE using redundancy, error-correcting codes (ECC), shielding, and fault-tolerant architectures. Nevertheless, the probability of SEE increases with altitude and during enhanced solar activity, particularly SEP and ground level enhancement (GLE) events [17].

In the context of the proposed measurement architecture, SEE-related radiation conditions are assessed using correlated measurements from both airborne and ground-based detectors. This allows a better description of the radiation environment used in SEE prediction models and supports their validation under real operational flight conditions. As a result, the system helps improve the accuracy of radiation risk assessment for aerospace electronic systems.

4. Intention – Onboard Radiation Measurement on JAS-39

The objective of the onboard radiation measurement campaign is to characterise the radiation environment encountered in military aviation using the JAS-39 Gripen platform. This study presents a measurement research proposal in which the aircraft is equipped with a semiconductor-based radiation detector, enabling future in-situ measurements of ionising radiation at flight altitudes. A ground-based detector is additionally deployed as a reference system for comparative analysis.

The primary objectives of the campaign are:

- to quantify radiation dose in a military aviation environment, with emphasis on altitude- and latitude-dependent variability;
- to characterise the particle field using a semiconductor detector system;
- to compare measured radiation levels with SWx and aviation radiation models;
- to reduce existing data gaps within SDA frameworks.

These objectives define the design drivers of the proposed experimental framework and will be addressed in future measurement campaigns following system deployment. The use of semiconductor detector technology enables both dose estimation and partial particle discrimination based on energy deposition signatures and event topology.

4.1 Experimental Design and System Architecture

The system is based on a semiconductor sensor module for ionising radiation detection. Its performance is constrained by the physical placement of the sensor within the aircraft, where structural shielding is present, as well as by the computational and memory limitations of the onboard unit and the capacity of the power system, which must ensure stable operation throughout the flight.

The design is optimised for the initial testing phase, with emphasis on maximising the use of the sensor's capabilities. No onboard data processing is performed; the system is dedicated solely to data acquisition and storage, while all post-processing is carried out externally. External mounting on the aircraft structure would be ideal; however, this is not feasible due to the requirement to avoid structural modifications and maintain full independence from aircraft avionics. Therefore, this option is not considered viable. Two alternative installation locations were evaluated: integration into the pilot's equipment or installation within the cockpit. The pilot-mounted configuration was rejected due to safety constraints in emergency scenarios and the lack of a stable and well-defined sensor orientation during flight, which would significantly complicate data analysis.

As a compromise, the measurement unit was installed in a side cockpit compartment originally designed for water storage. Although not optimal from a measurement perspective, this location is considered sufficient for the pilot phase and enables acquisition of usable and representative data.

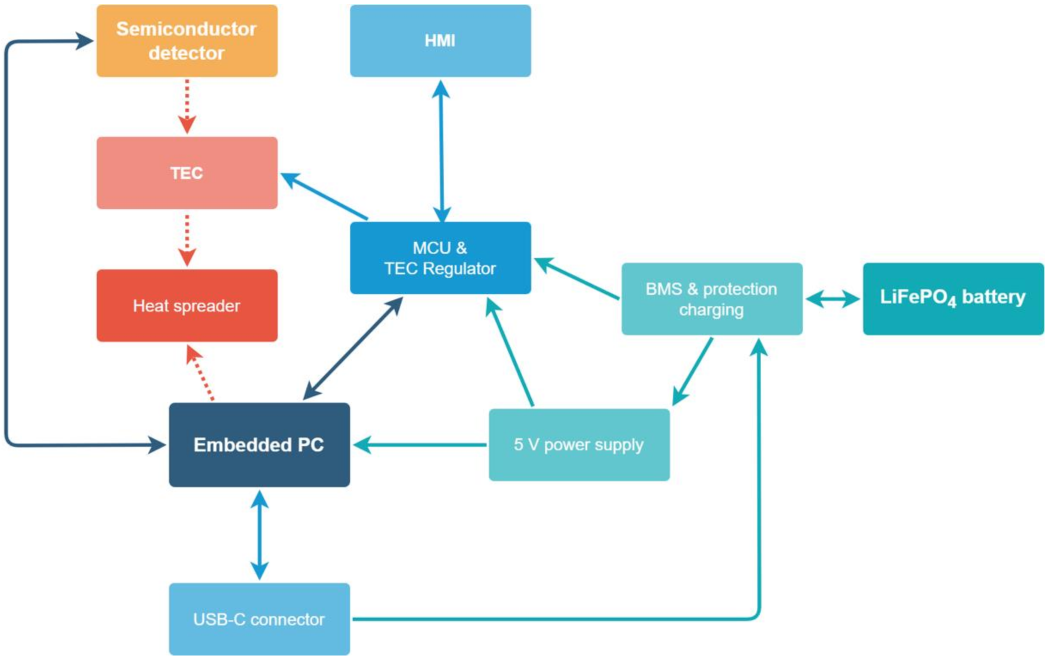

Fig. 1 Block diagram of the proposed airborne radiation measurement system, illustrating the integration of the semiconductor detector, thermal management subsystem (TEC and heat spreader), control unit (MCU), data acquisition unit (embedded PC), human–machine interface (HMI), and power management subsystem including BMS, 5 V supply, and LiFePO$_4$ battery.

The system (Fig. 1) is powered by a rechargeable battery pack charged on the ground. It is designed for a single mission with an operational endurance of approximately 3 hours, including reserve capacity. A LiFePO$_4$ battery with a capacity of 50 Wh was selected, providing sufficient energy for standard operational and ferry flights. LiFePO$_4$ technology was chosen due to its intrinsic safety characteristics, availability with ATEX certification, and established use in military applications. Together with implemented overcurrent, overvoltage, and thermal protection mechanisms, the system achieves a high level of operational safety.

The measurement unit complies with relevant standards for electrical safety and electromagnetic compatibility. No wireless communication interfaces are included in the system, including GNSS receivers. Charging, data transfer, and real-time clock synchronisation are performed via a USB-C interface. The recorded data consist solely of semiconductor sensor measurements and timestamps. From the perspective of the aircraft, the dataset is fully independent and anonymous. Any correlation with aircraft position or other onboard systems is only possible in post-processing using time synchronisation.

4.2 Proposed methodology

The proposed system consists of two identical semiconductor radiation detectors. One detector operates as a reference unit in a controlled laboratory environment, providing continuous monitoring of background radiation and instrument stability. The second detector is integrated into a mobile airborne system onboard the JAS-39 Gripen aircraft, enabling in-flight measurements across different operational flight regimes.

Once operational, measurements are expected to be conducted on a daily basis, with a total acquisition time of approximately 3 hours per mission. Prior to deployment, both detectors are time-synchronised to ensure consistent response and direct comparability of recorded data. After each flight, the airborne system is connected to a docking station for data transfer and storage, while the reference detector continues continuous background monitoring for stability assessment. Radiation data are recorded at a defined temporal resolution using a shared time reference, ensuring full temporal consistency between airborne and ground-based measurements. SWx conditions are characterised using publicly available datasets, which provide contextual information for interpretation of the measured radiation field.

4.3 Data Collection and Evaluation

Radiation data are recorded at a fixed temporal resolution. Following system implementation, the dataset will be evaluated in combination with complementary sources, including onboard aircraft instrumentation and external SWx observations. Data processing and interpretation are performed in a dedicated post-processing phase. This enables correlation of radiation measurements with operational flight parameters and prevailing SWx conditions, supporting a comprehensive analysis of the measured radiation environment.

5. Expected Results

The implementation of the proposed measurement activities is expected to provide a valuable and operationally relevant source of SWx data, contributing to NATO capability development and improved environmental awareness in the aviation domain. The resulting dataset will enhance situational awareness and significantly improve the spatial and temporal coverage of SWx observations across operational environments.

The collected measurements will enable improved characterization of the space radiation environment, including identification of altitude-dependent variations in radiation levels under real flight conditions. This will provide empirical data that is currently limited in existing global monitoring and modelling systems.

In addition, the dataset will be shared with the Military University Hospital to support more accurate assessment of radiation exposure, particularly for aviation personnel operating at high altitudes. The measurements will also support evaluation of radiation effects on onboard aircraft electronics, with respect to varying particle composition and SWx conditions.

Furthermore, the proposed framework will contribute to the validation and refinement of existing radiation models and support the development of improved predictive tools for SWx forecasting. Overall, the expected results will strengthen the empirical basis for radiation assessment and enhance the operational applicability of SWx information in military aviation.

6. Conclusions

This study presents a structured experimental framework for in-situ measurement of ionising radiation in military aviation using a JAS-39 Gripen platform equipped with a semiconductor detector system and a ground-based reference unit. The work defines a measurement research proposal and experimental design, establishing the foundation for future operational implementation rather than reporting completed measurements.

The proposed methodology enables temporally synchronised radiation measurements under realistic flight conditions. Once implemented, it will support systematic comparison with SWx observations, operational forecasts, and radiation exposure models, including AVIDOS. By integrating these data sources, the framework provides a multi-layer validation approach that addresses the current lack of high-resolution in-situ observations in aviation-relevant altitude regimes. The expected outcome is a strengthened empirical basis for characterising radiation variability in near-Earth space and improving the reliability of SWx modelling in aviation contexts. Overall, the proposed research proposal contributes to SDA by enabling a scalable and operationally relevant approach to radiation monitoring in military aviation environments.

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