

Article

UAV-Based Survey of the Equivalent Dose Rate Distribution Above the Outer Cladding of the Chornobyl New Safe Confinement Following Damage

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Highlights

What are the main findings?

- UAV-based radiation mapping was successfully applied to the damaged outer cladding of the Chornobyl New Safe Confinement (NSC) under real post-incident operational constraints.
- The equivalent gamma dose rate above the surveyed NSC area was spatially non-uniform, with the highest rates observed near and above the Shelter Object rather than at the main detonation-related damage zone.

What are the implications of the main findings?

- The results demonstrate that UAV-based radiation surveys can rapidly provide spatially resolved radiological information to support repair planning and operational decision-making in hazardous and inaccessible nuclear facilities.
- The study extends the practical use of UAV radiation mapping from open terrain to complex large-scale engineering structures, where direct human access is restricted by radiological and physical hazards.

Abstract

On 14 February 2025, the outer cladding of the Chornobyl New Safe Confinement (NSC) was damaged by an explosion caused by a one-way attack unmanned aerial vehicle (UAV), creating a hole of about 15 m in diameter and requiring about 300 penetrations to be made in the cladding during firefighting. This created an urgent need to assess radiation dose rates above damaged areas to support repair planning and worker radiation protection. This study presents a UAV-based survey of the equivalent gamma dose rate distribution above the damaged northern side of the NSC outer cladding. The survey used a bespoke system, integrating a multirotor UAV, an AccuRad Personal Radiation Detector (PRD), onboard data acquisition and transmission modules, and ground-based and server-side analytical components. Measurements were performed under real post-incident field conditions, including restricted flight zones, wind-induced turbulence, proximity to large metallic structures, and electronic warfare interference. The dataset was filtered for Global Positioning System (GPS) reliability, transformed into a metric coordinate system, and



Academic Editor: Arianna Pesci

Received: 28 June 2026

Revised: 20 July 2026

Accepted: 23 July 2026

Published: 24 July 2026

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processed for spatial interpolation and mapping. The resulting distribution showed a spatially non-uniform radiation field: the main damage zone had relatively low equivalent gamma dose rates, whereas the highest values, up to 1092 $\mu\text{Sv/h}$, were recorded over areas of the NSC closest to the Shelter Object. The study demonstrates UAV-based radiation mapping of a damaged large-scale confinement structure and provides data supporting Chernobyl Nuclear Power Plant repair planning.

Keywords: UAV-based radiation survey; hardware-software system; georeferenced sensing; spatial data fusion; data-driven radiation mapping; decision support systems; Chernobyl New Safe Confinement

1. Introduction

On 14 February 2025, the outer cladding of the Chernobyl Nuclear Power Plant (ChNPP) New Safe Confinement (NSC) was damaged following a strike by a one-way attack unmanned aerial vehicle (UAV) and its subsequent detonation. The explosion caused a fire inside the cladding interspace, which spread due to the combustion of the sealing membrane within the thermal insulation layers. Fire localisation and suppression required multiple openings of the outer cladding at locations where heat sources had been identified using a thermal imager mounted on a UAV. The damage and subsequent firefighting operations compromised structural aspects of the NSC, including those related to the isolation of the Shelter Object from the surrounding environment and the intended 100-year service life of the structure. The cladding was ruptured in approximately 300 locations, with a hole around 15 m in diameter at the point of UAV detonation.

Before repairs to the damaged sections of the NSC structure could commence, it was necessary to characterise the radiological conditions in and around the affected area. A gamma dose mapping assessment was therefore urgently undertaken to determine whether human workers could be safely deployed to carry out the required repairs. The results of this assessment were intended to inform not only the feasibility of manual intervention, but also the optimisation of workforce deployment, including the number of personnel involved and the duration of their exposure, to ensure that repairs could be completed while maintaining radiation doses within acceptable limits.

Direct worker access to the damaged sections of the outer cladding is significantly constrained due to risks posed by both working at height on the surface of a damaged building structure and gamma radiation exposure arising from the Shelter Object contained within the NSC. Under such conditions, UAV-based remote survey methods represent a logical and practically justified solution for conducting a gamma dose mapping assessment without the need for direct worker involvement in the hazard area.

UAVs are already widely used for remote radiation surveys of contaminated land areas, nuclear legacy sites, and other restricted-access areas. Their reported application includes source localisation, dose-rate mapping, and rapid data acquisition after accidents or other abnormal events, using both low-cost and rapidly deployable measurement platforms [1–15]. However, most published studies concern open terrain, contaminated land, or relatively simple surfaces, where flight geometry, source-to-detector configuration, and spatial sampling can be controlled more easily and flights repeated if necessary. In parallel, recent UAV research has shown that trajectory design, low-altitude path planning, and structured data-acquisition strategies can substantially improve sampling consistency, safety, and data quality for large-scale inspection and mapping tasks [16–18]. More generally, the reliability of UAV-derived geospatial products is strongly influenced by the adopted acquisition and positioning strategy, especially in constrained operating environ-

ments [19]. These approaches, however, generally assume that the mission can be planned and executed under controlled conditions.

The outer cladding of the NSC represents a very different survey challenge from those commonly described in the literature. It is a large and curved engineering structure located above a complex radiation field generated by the radioactive materials contained within the Shelter Object. This creates a complex measurement geometry, limited possibility for regular near-surface sampling, and strong dependence of the survey result on flight constraints and structural context. The present survey was further distinguished by its post-incident character and by the severe operational conditions under which it had to be performed. This included restricted flight zones, wind-induced instability, close-range operation near damaged cladding, magnetic interference from ferrous materials, and electronic warfare effects. As a result, the survey geometry represented a compromise between the ideal measurement concept and the flight conditions that were actually achievable in the field at the time of deployment.

Against this background, the contribution of the present work is twofold. First, it provides the first direct survey-derived dataset characterising the equivalent gamma dose rate field above the damaged outer cladding of the Chornobyl New Safe Confinement, beyond the limited-extent roof-walkway zone where routine measurements had previously been available. This represents the first acquisition of primary radiation-field data for a post-incident structural configuration that could not be investigated during the design and construction of the NSC, since the Arch was assembled in a separate area and only later moved into its final position over the Shelter Object. Second, it demonstrates a practical workflow for obtaining georeferenced radiation data over a complex large-scale confinement structure under severe operational constraints.

The aim of this paper is therefore not only to present the resulting radiation map, but also to show how such data can be acquired, filtered, interpreted, and used to support repair planning and radiation protection decision-making under real field conditions.

The remainder of this paper is organised as follows. Section 2 describes the UAV-based survey system, its hardware and software architecture, and the measurement and data-processing methods. Section 3 presents the conditions, equipment, and procedures of the survey campaign. Section 4 reports the processing and validation of the primary dataset, the resulting spatial distribution of equivalent gamma dose rate, and the principal methodological limitations. Section 5 summarises the main findings and their practical implications.

2. Equipment and Methods

2.1. UAV-Based Remote Radiation Survey System

The survey was carried out using a detector-integrated lightweight UAV system that combined technological solutions developed by the DOZOR hardware and software (DOZOR software 0.1, IMMSP, Kyiv, Ukraine) complex, originally created by the Institute of Mathematical Machines and Systems Problems of the National Academy of Sciences (NAS) of Ukraine (Kyiv, Ukraine) with the participation of experts from the Institute for Safety Problems of Nuclear Power Plants (ISPNNP) of the NAS of Ukraine (Chornobyl, Ukraine). The system also incorporated technological developments and radiation-detection components obtained under the NATO Science for Peace and Security (SPS) G5913 project, Enhanced Radiation Detection for Nuclear Security and Incident Response, by researchers from ISPNNP of the NAS of Ukraine and the University of Bristol, United Kingdom.

Although the DOZOR prototype had been developed earlier within a different research framework, the present study represents its first real-world deployment for a post-incident radiation survey of the damaged outer cladding of the Chornobyl New Safe Confinement.

In this work, the system was adapted to the specific operational requirements of the NSC survey, including integration with the selected dosimeter, deployment on different UAV carrier platforms, and application under severe field constraints associated with restricted flight zones, wind effects, and electronic warfare interference.

Since the DOZOR radiation mapping prototype has not been described in the open literature, its main characteristics are briefly presented below.

The mapping system is intended for operational remote radiation surveys of territories and facilities deployed on multirotor UAV platforms. Its principal feature is the independence of the measurement payload and onboard recorder architecture with respect to the UAV carrier platform. This allows deployment of the system on different UAV types capable of carrying a payload exceeding 500 g. The onboard recorder installed on the UAV enables integration with various types of dosimetric instruments equipped with digital interfaces, including both specialised and individual dosimeters. The system is designed for rapid deployment and operation under limited-resource conditions.

2.2. Technical Architecture of the DOZOR System

The system consists of three main components:

- The airborne UAV mapping payload;
- The operator ground station;
- The server-based analytical unit.

2.2.1. Airborne Subsystem

With the exception of the radiation detector itself, the airborne subsystem was based primarily on commercially available electronic components rather than on dedicated radiation-hardened hardware. This was an intentional design choice reflecting the practical objective of rapid deployment under limited-resource emergency conditions.

In this deployment concept, the airborne platform was treated as a replaceable field asset rather than as a long-endurance radiation-hardened system. No radiation-induced failures of the onboard electronics were expected during the reported survey campaign, based on rough pre-mission engineering judgement that took into account the planned exposure duration, stand-off distance from the Shelter Object, and prior practical experience with similar commercially available electronics in comparable field conditions.

At the same time, the present study did not specifically evaluate the long-term radiation tolerance of the airborne electronics, and this should be regarded as outside the scope of the reported work.

The UAV payload includes:

1. An onboard recorder, comprising:
 - a. A communication and computing unit based on a Raspberry Pi Zero 2 WH microcomputer (Raspberry Pi Ltd., Cambridge, UK);
 - b. A positioning subsystem based on a Global Navigation Satellite System (GNSS) GPS module with Real-Time Kinematic (RTK) functions;
 - c. A LoRa-based data transmission module;
 - d. A photo-recording subsystem based on a fisheye-type video camera integrated with the onboard microcomputer.
2. A dosimeter with a digital interface. In the present work, a Mirion AccuRad Personal Radiation Detector (PRD) (Mirion Technologies, Inc., Atlanta, GA, USA) was integrated, and integration with Hamamatsu spectrometers (Hamamatsu Photonics K.K, Shizuoka, Japan) and several Ukrainian Ecotest dosimeters (ECOTEST GROUP, kviv, Ukraine) has also been achieved.

3. A mounting module adapted for different UAV types, including DJI Mavic, Autel, and custom-built First-Person View (FPV) platforms.

The onboard recorder is augmented with a wired data connection to the drone flight controller utilising the MAVLink protocol.

2.2.2. Ground Subsystem: Operator Ground Station

The operator ground station is based on a portable computer running Windows 10 with the DOZOR software installed. The station is equipped with an external LoRa transceiver (Waveshare Electronics, Shenzhen, China) and a GNSS RTK Base module equipped with a ZED-F9P receiver (u-blox AG, Thalwil, Switzerland).

Its main functions are:

- Reception and recording of measurement data;
- Visualisation of current parameters;
- Storage of survey results;
- Operational control of the survey process.

2.2.3. Server-Based Analytical Unit

The server-based analytical unit is implemented as a Linux server performing the following functions:

- Formation of the survey database;
- Long-term storage of results;
- Analytical and computational processing for mapping and data analysis.

2.3. Software Architecture and Data Flows

When operating, the UAV payload records data packets at a 1 Hz rate, containing information on the measured equivalent gamma dose rate, geospatial coordinates, and an image of the surface beneath the drone at the time of measurement.

In real time, a 'reduced' data packet containing information on the current equivalent gamma dose rate and the geospatial coordinates of the UAV is transmitted via the LoRa communication channel to the ground station. Image data are not transmitted via LoRa due to data bandwidth constraints. The same LoRa channel is also used to transmit RTK correction signals from the GNSS base station to the airborne payload.

The communication architecture was designed on the assumption that reliable real-time transmission could be degraded under field conditions. Therefore, the complete dataset is stored in the local database on the airborne payload, while the LoRa channel is reserved for basic operational data and RTK corrections.

When the UAV returns to within reliable Wi-Fi range of the ground station (<50 m), the locally stored data are automatically replicated to the ground station database. Data replication from the UAV to the ground station can also be initiated manually.

When communication between the ground station and the server-based analytical unit is available, the data are copied onwards to the global database on the secure server. The server provides analytical users with access to the survey information through a web application. In addition, the server hosts dedicated software for enabling data fusion, filtering and error correction, as well as other mathematical processing procedures, including data interpolation. The system also supports data export to external Geographic Information System (GIS) software platforms.

The structural schema for the hardware and software is depicted in Figure 1. Arrows indicate the corresponding data flows.

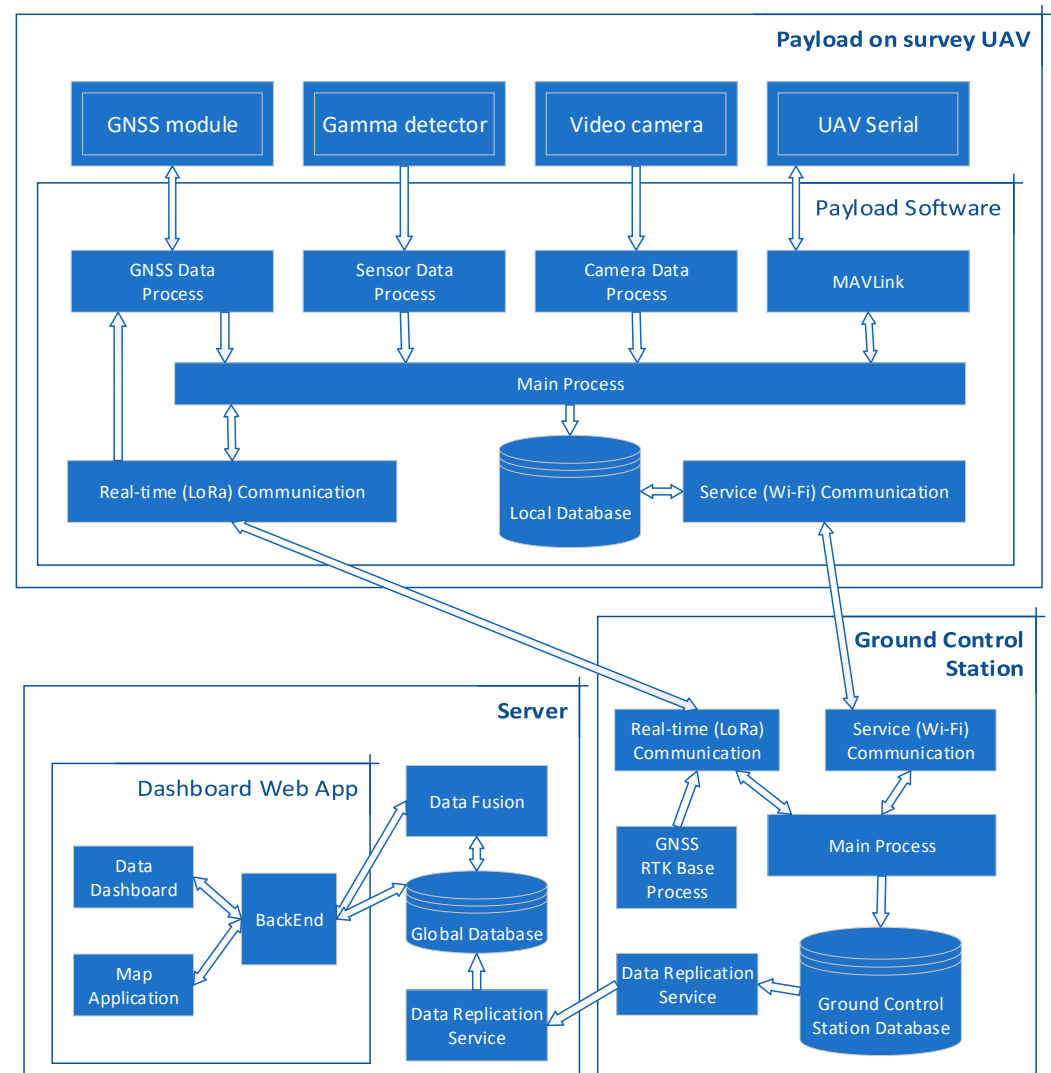


Figure 1. Overall software architecture and data flows of the DOZOR system; the arrows depict the specific directions of data flows between the survey UAV payload, ground control station, server-based analytical unit, and their internal modules.

2.4. Measurement and Data-Processing Methods

Two scenarios were considered for the gamma radiation survey of the NSC's outer cladding: an ideal scenario and a contingency scenario.

The ideal scenario included two measurement series. The first series consisted of a survey of the damaged northern side of the NSC along a route formed by a sequence of parallel lines aligned with the NSC's long axis, with a spacing of 10 m and a flight height of 1 m above the cladding surface. The second series consisted of flights over the damaged areas with hovering for 15 s above selected points of interest in order to collect a statistically enhanced set of gamma measurements and to obtain photographic documentation of the corresponding area of damage.

The contingency scenario consisted of flights above the NSC's outer cladding along the central long axis of the NSC over the man-accessible service platform area, where the gamma radiation profile was already known, followed by additional flights over those parts of the NSC where the operator was able to maintain stable UAV controllability.

Initially, the general approach to constructing the observation network for subsequent interpolation over the northern part of the NSC surface assumed the collection of equivalent

gamma dose rate readings within an area of 1 m², followed by filtering with respect to measurement height and averaging of the recorded values.

Later, in order to obtain the most conservative dose estimates, it was decided to use the maximum recorded equivalent gamma dose rate value rather than the averaged value.

The possible influence of detector response time and internal signal processing on the spatial attribution of measurements was also considered. In an earlier study involving a different equivalent gamma dose rate detector operated dynamically above the Shelter Object, members of the author team identified a measurable delay associated with internal microprocessor processing and numerical filtering, which displaced the apparent position of radiation-field changes during detector motion [20]. This previous experience was taken into account when interpreting the present dataset.

For the AccuRad PRD used in this study, the manufacturer does not disclose either the proprietary signal-processing algorithms or the parameters required to determine the effective integration time, rise time, or filtering delay. However, unlike the detector used in the earlier study, the AccuRad PRD provides access to both the processed equivalent gamma dose rate and the count rate in counts per second (CPS). Preliminary bench checks using available laboratory radiation sources showed consistent changes in CPS and reported equivalent gamma dose rate, together with a prompt qualitative response to changes in source–detector geometry. These observations did not indicate an obvious long-duration lag comparable to that encountered in the earlier detector system, but they were not intended as a dedicated quantitative characterisation of the detector’s dynamic response.

Because the payload recorded data at 1 Hz, the spatial relevance of each record depended on UAV motion at the time of measurement and on the detector’s effective response characteristics. The survey was therefore planned around slow close-range flying at approximately 1 m/s, corresponding under the intended operating conditions to a nominal displacement of about 1 m between consecutive measurements, together with visually controlled hovering or near-hovering whenever possible. Rapidly changing UAV position was treated as one of the practical indicators in data-quality filtering, since under such conditions a measured equivalent gamma dose rate value could not be confidently attributed to a narrowly localised surface area. The absence of a dedicated quantitative characterisation of the AccuRad PRD’s dynamic response under actual flight conditions remains a limitation of the present study.

Two interpolation approaches were examined during data processing. Linear interpolation was adopted as the principal method for generating the final equivalent gamma dose rate maps. Kriging was used only as an exploratory consistency check to assess whether the resulting spatial pattern was qualitatively similar to that obtained by linear interpolation. Because kriging was not used as the primary estimation method in the reported workflow, no formal variogram-based optimisation or cross-validation procedure was applied in the present study.

The final output of the data-processing chain is an interactive heatmap showing the equivalent gamma dose rate distribution over the surface of the northern part of the NSC’s outer cladding.

3. Description of the Survey Campaign

3.1. Conditions of the Survey Campaign

The UAV survey was conducted in an operationally complex post-incident environment. Flight operations had to be performed only within strictly limited zones approved by the ChNPP administration. As a result, both the accessible routes and the set of possible hovering points were constrained in advance by administrative and safety requirements.

These restrictions had to be taken into account together with the geometric complexity of the NSC structure and the need to approach the damaged roof area at short stand-off distances.

From a practical point of view, the most important environmental factor for the flight campaign was wind (speed, direction and turbulence), since even moderate gusts affected the ability of the UAV to maintain a stable position near the cladding surface. This directly influenced the achievable hovering time, the distance between the detector and the surface, and, consequently, the spatial consistency of the measurements. Therefore, the recorded survey data should be regarded as the best possible under field conditions rather than as a fully controlled measurement setup.

In addition to meteorological factors, the survey was performed under operational limitations typical of the ChNPP site during wartime. These limitations affected the choice of flight windows, route planning and the feasibility of repeated measurements over the same area. Consequently, the resulting dataset reflects a compromise between the desired measurement geometry and the practically achievable flight conditions.

3.2. UAV Platforms and Measurement Equipment

Equivalent gamma dose rate measurements above the damaged outer cladding of the NSC Arch were performed using an AccuRad PRD dosimeter integrated with the airborne data acquisition module of the developed UAV-based survey system. The AccuRad is a high-sensitivity personal radiation detector designed for emergency response, law enforcement and military use. According to the manufacturer's specification, the dosimeter provides equivalent gamma dose rate measurements in the range from 0.1 $\mu\text{Sv/h}$ to 10 Sv/h and records accumulated gamma dose up to 10 Sv. Gamma registration is performed in the energy range from 25 keV to 10 MeV using a built-in CsI(Tl) scintillation detector coupled with a temperature-compensated silicon photomultiplier and a silicon diode. The instrument is equipped with Bluetooth/Near-Field Communication (NFC) wireless interfaces and a USB Type-C port. This makes it suitable for integration with the onboard recorder independently of the selected UAV carrier platform. In the present study, the choice of this dosimeter was primarily determined by its support for Bluetooth data transfer and its wide measurement range up to 10 Sv/h.

For the initial flights, a DJI Mavic 3 Pro quadcopter (SZ DJI Technology Co., Ltd., Shenzhen, China) was selected as the carrier platform. This UAV provided advanced in-flight stabilisation and built-in telemetry capabilities that were expected to improve the positional referencing of the equivalent gamma dose rate measurements. To install the dosimeter and communication equipment, a dedicated mounting module was designed and manufactured specifically for this platform. Several versions of the mounting module were produced using 3D printing; the final version was selected as the most practical because it did not obstruct the downward-looking onboard cameras used by the operator for close-range positioning near the NSC cladding.

However, the use of the DJI Mavic 3 Pro was limited only to the first flights. The subsequent survey flights were performed using a bespoke FPV UAV platform. The transition to the bespoke FPV UAV platform was driven by the actual operating conditions in the Chernobyl Exclusion Zone, including the influence of electronic warfare effects that reduced the reliability of GNSS-dependent flight functions and confidence in automated navigation and stabilisation. Under these conditions, a bespoke FPV UAV platform operated manually by an experienced pilot was considered more suitable for continuing the survey. This transition did not alter the core measurement payload, but it did affect the achievable flight geometry and hovering capability.

Thus, the survey campaign combined two carrier solutions: a commercial quadcopter at the initial stage and a bespoke FPV UAV platform for the survey campaign under

constrained field conditions. This transition demonstrated the portability of the survey payload between different UAV platforms, although the flight performance and operational constraints remained platform-specific.

3.3. Survey Procedure

The survey concept assumed slow motion, approximately walking speed (~ 1 m/s), together with hovering or near-hovering where possible over strategic locations.

During the first flight, a reconnaissance pass was performed above the roof walkway located in the upper part of the NSC and extending along the entire structure from east to west. This was followed by a series of close-range flights near the NSC cladding in order to assess UAV controllability under wind flow conditions around the Arch. After that, at the request of ChNPP representatives, the flight objectives were shifted towards visual inspection and photography of the damaged cladding areas (see Figure 2). As a result, the equivalent gamma dose rate measurements were carried out according to a contingency survey scenario rather than the initially intended measurement scheme.

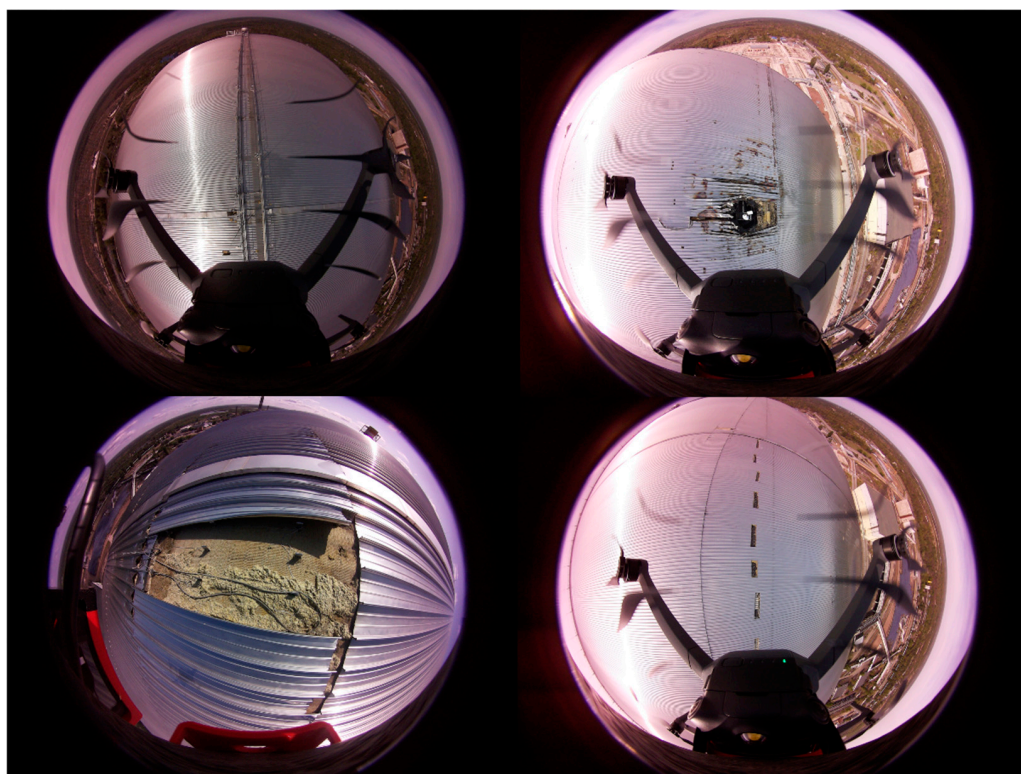


Figure 2. Photographs of the damaged cladding recorded during the survey flight.

The subsequent flights performed using the bespoke FPV UAV platform were also conducted according to the same contingency scenario. Because the UAV was operated manually, without GNSS-based or optical stabilisation, the pilot visually maintained the flight altitude within approximately 1–3 m above the NSC's outer cladding in order to avoid collision with the structure while preserving short stand-off distances. Most of the flight time was devoted to the damaged sections of the outer cladding and the surrounding areas of interest. Considerable attention was given to repeated flyovers around the main detonation-related damage zone in the outer cladding in order to perform detailed visual inspection. At the same time, the use of the FPV platform made stable hovering at a fixed point more difficult, which reduced the possibility of collecting a statistically representative series of repeated measurements at the same location.

All measurement data were transmitted to the ground station in real time and, simultaneously, saved onboard the UAV mapping payload as a backup in case of data transmission failures. It should also be noted that the 10 s photo acquisition interval was originally selected for the ideal survey scenario and was not modified during the actual flights.

4. Results and Discussion

4.1. Primary Dataset and Data Processing

As a result of the survey of the NSC's outer cladding, a primary dataset of equivalent gamma dose rate values was obtained for the northern part of the NSC Arch. The dataset covered not only the area directly above the main opening formed by the detonation-related destruction of the outer cladding, but also the areas above the additional openings created during firefighting operations.

Positional quality control of the primary dataset was performed using a hybrid workflow combining automatic screening and expert-based verification. During the available flight windows, RTK-level positioning could not be achieved by the airborne payload. Independent coordinate verification using carrier-UAV navigation data was not possible, because the GPS function of the DJI carrier platform was intentionally disabled as a countermeasure against GPS spoofing, while the FPV platform was not equipped with a GNSS receiver.

At the first stage, all records outside the defined survey area were excluded automatically. At the second stage, the remaining records were reviewed using a dedicated software tool that visualised the flight path on a simplified 3D model together with UAV position, measured equivalent gamma dose rate values, and time-synchronised photo information. Records whose positional validity could not be confirmed by expert review were excluded from further analysis. Expert verification relied on time-synchronised photo and video documentation of the UAV position relative to identifiable NSC structural elements, including characteristic damage features of the NSC outer cladding.

For a limited subset of measurements, positional assignment was manually refined using time-synchronised photo and video records and the simplified 3D flight-path visualisation, where sufficient confidence could be achieved by reference to identifiable NSC structural elements. The resulting dataset should therefore be regarded as a filtered and expert-verified positional dataset rather than as a purely GNSS-derived trajectory. This procedure reflects the emergency field conditions of the survey campaign and should be considered a source of residual spatial uncertainty.

After filtering, the coordinates were transformed into the metric coordinate system of the horizontal projection of the northern part of the NSC Arch. This transformation was based on the adopted geometric representation of the NSC and on identifiable structural reference features visible in the synchronised survey imagery. Because RTK-level positioning was not achieved during the campaign, the resulting spatial alignment should be regarded as operational rather than geodetically precise. The spatial distribution of the retained records and the corresponding local sampling density are shown in Figure 3. The figure presents both the individual measurement positions and the number of records within each occupied 1 m² cell. This representation allows the spatial support of the subsequent interpolation to be assessed directly and distinguishes densely surveyed areas from regions represented by isolated or sparsely distributed measurements.

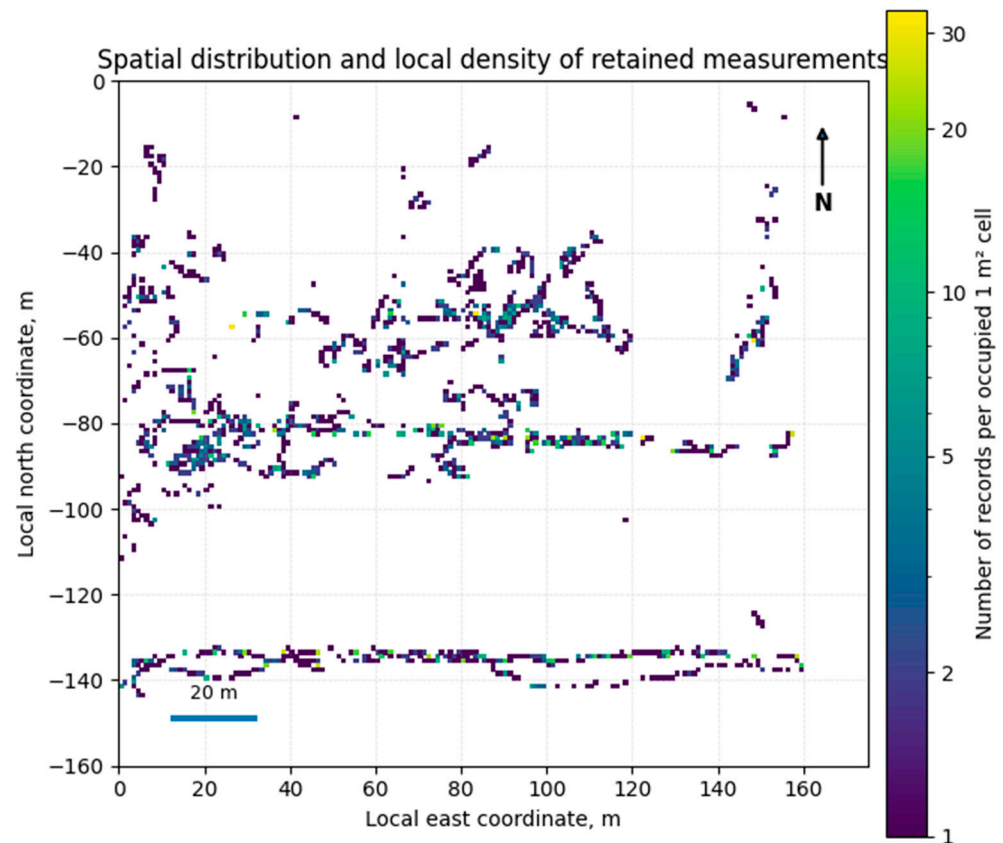


Figure 3. Spatial distribution of the retained measurement records used for interpolation. Points show the positions of the retained UAV measurements, while the 1 m² cell grid indicates local sampling density. The colour scale is logarithmic to improve the distinction between sparsely and densely sampled cells. Coordinates are shown in the local metric reference frame, with north oriented upwards.

An additional consistency check was performed along the central roof walkway that runs along the apex-line of the NSC Arch, where independent handheld measurements were recorded at 6 m intervals (Figure 4). Two UAV survey series acquired above the same reference transect were compared with data recorded using a handheld device using both average-based and maximum-based cell values.

The agreement was quantified using five complementary metrics summarised in Table 1: the Pearson correlation coefficient, mean absolute error (MAE), root mean square error (RMSE), mean signed error (bias) and range-normalised root mean square error (NRMSE). Pearson's coefficient was used to characterise similarity in the spatial shape of the profiles, whereas MAE and RMSE quantified the magnitude of the differences between the UAV-derived and handheld values. Bias was calculated as the mean signed difference between the UAV-derived and corresponding handheld measurements, with positive values indicating overestimation by the UAV-derived profile. NRMSE was calculated by normalising RMSE to the range of the handheld reference profile:

$$\text{NRMSE} = \frac{\text{RMSE}}{R_{\max} - R_{\min}} \times 100\% \quad (1)$$

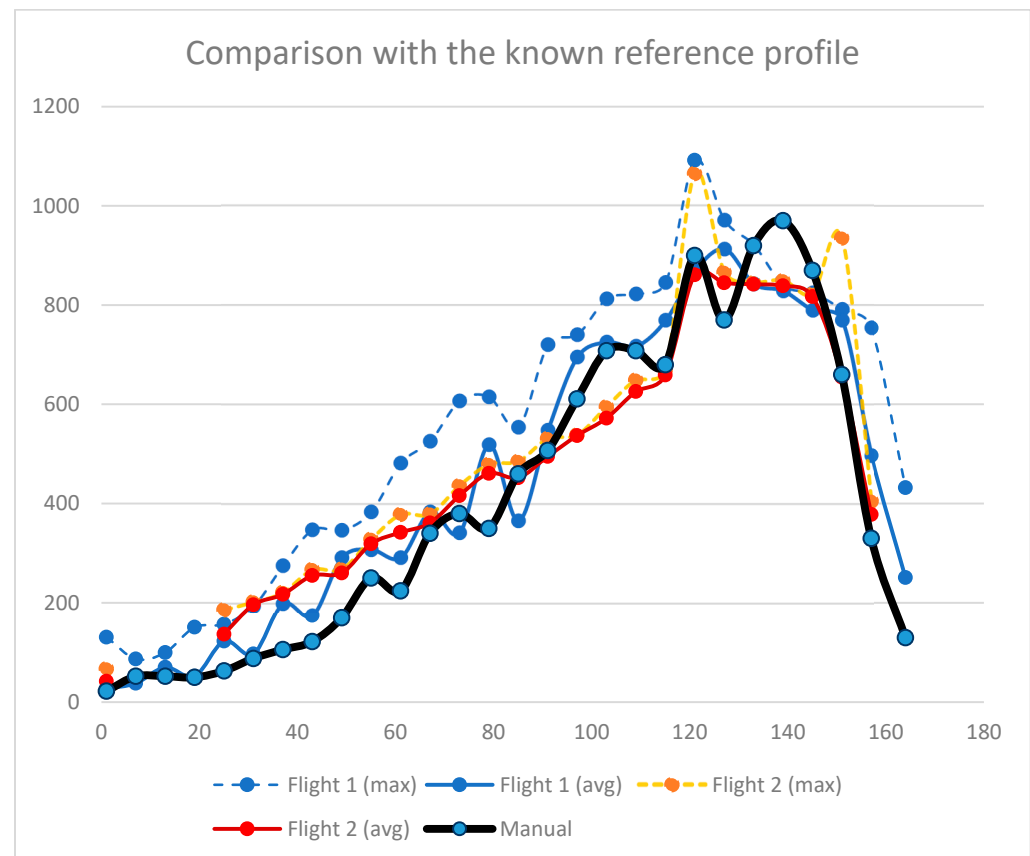


Figure 4. Comparison of the equivalent gamma dose rate profile measured manually along the roof walkway of the NSC Arch (6 m spacing) with two UAV-derived profiles obtained over the same reference transect. Solid lines show the manual profile and UAV average-based profiles; dashed lines show the corresponding conservative maximum-based UAV profiles. The x-axis shows distance in metres from the western end of the NSC, and the y-axis shows equivalent gamma dose rate in $\mu\text{Sv/h}$.

Table 1. Quantitative comparison of UAV-derived equivalent gamma dose rate profiles with the independent handheld reference profile along the NSC roof walkway.

UAV-Derived Profile	Matched Positions, (n)	Pearson (r)	MAE, $\mu\text{Sv/h}$	RMSE, $\mu\text{Sv/h}$	Bias, $\mu\text{Sv/h}$	NRMSE, %
Flight 1, average-based	28	0.968	69.9	85.5	+35.8	9.0
Flight 1, maximum-based	28	0.937	156.5	179.7	+143.8	19.0
Flight 2, average-based	24	0.980	68.9	80.4	+15.6	8.5
Flight 2, maximum-based	24	0.948	94.0	109.6	+52.3	11.6

For the handheld reference profile, $(R_{\text{max}} - R_{\text{min}})$ was $948 \mu\text{Sv/h}$. All metrics were calculated only for positions at which both UAV-derived and handheld measurements were available.

The results showed that the average-based UAV profiles were in closer quantitative agreement with the handheld measurements than the corresponding maximum-based profiles. For flights 1 and 2, respectively, the average-based profiles produced Pearson correlation coefficients of 0.968 and 0.980, RMSE values of 85.5 and $80.4 \mu\text{Sv/h}$, and range-normalised RMSE values of 9.0% and 8.5%. Their positive bias values of 35.8 and $15.6 \mu\text{Sv/h}$ indicate moderate systematic overestimation.

The maximum-based profiles exhibited larger MAE and RMSE, and positive bias values, which is consistent with their intended role as a conservative representation of the radiation field. Nevertheless, their Pearson correlation coefficients remained high, indicating that the principal spatial pattern of the reference profile was preserved. Thus, the average-based profiles more closely reproduced the absolute handheld measurements, whereas the maximum-based profiles retained the overall spatial trend while providing systematically more conservative values. This quantitative comparison supports the physical credibility of the UAV-derived radiation distribution within the reference zone of the NSC structure.

Thus, the following data-processing sequence was implemented: acquisition of primary measurements, positional quality control, transformation into a metric coordinate system, formation of the survey database and subsequent processing and interpolation to form gamma dose rate maps. This approach made it possible to move from a set of discrete measurement points to an integral representation of the radiation field above the surveyed part of the NSC outer cladding.

4.2. Spatial Distribution of Equivalent Gamma Dose Rate Above the NSC Outer Cladding

The processed dataset was then further used for interpolation and visualisation of the equivalent gamma dose rate distribution. A two-dimensional linear interpolation was performed on the unstructured dataset, and the results were presented in the form of a heatmap. This type of visualisation made it possible to represent the measurement results as a two-dimensional field in which the colour scale corresponds to the transition from lower to higher equivalent gamma dose rate values. A separate map outlining the locations of the damaged areas was generated separately.

The resulting map showed that the equivalent gamma dose rate distribution above the northern part of the NSC outer cladding is spatially non-uniform, reaching up to $1092 \mu\text{Sv/h}$ in those areas located closest to the Shelter Object (see Figure 5). Importantly, the main detonation-related damage zone itself was characterised by relatively low equivalent gamma dose rate values, typically in the range of $30\text{--}50 \mu\text{Sv/h}$. This area received the densest measurement coverage during the campaign because it was the primary target of detailed visual inspection. The observed low-dose pattern in this region is consistent with the fact that the impact of the attacking UAV occurred in the area of the NSC Arch where the northern garage is located, i.e., the maintenance area of the main crane system trolleys, which has its own bioshield and is located at a considerable distance from the Shelter Object. This interpretation is also supported by independent handheld measurements obtained in the same area.

It is inferred that the measured spatial variation in equivalent gamma dose rate over the NSC Arch is governed primarily by the influence of the Shelter Object rather than by the damaged cladding areas themselves.

Accordingly, the heatmap-based gamma dose rate visualisation made it possible to obtain, in an operational manner, an integral view of the radiation field over the entire plane of the northern part of the NSC Arch. As shown in published studies [3–5,9,11], this type of gamma heatmap representation is widely used for mapping territories contaminated with radionuclides or other hazardous substances released into the environment as a result of industrial activities or accident conditions. In the present case, however, the same visualisation approach was applied not to open terrain but to the outer cladding of the NSC—a large engineering structure—which represents a notably more complex measurement task, especially given the pronounced heterogeneity of the gamma radiation field and its high intensity in places.

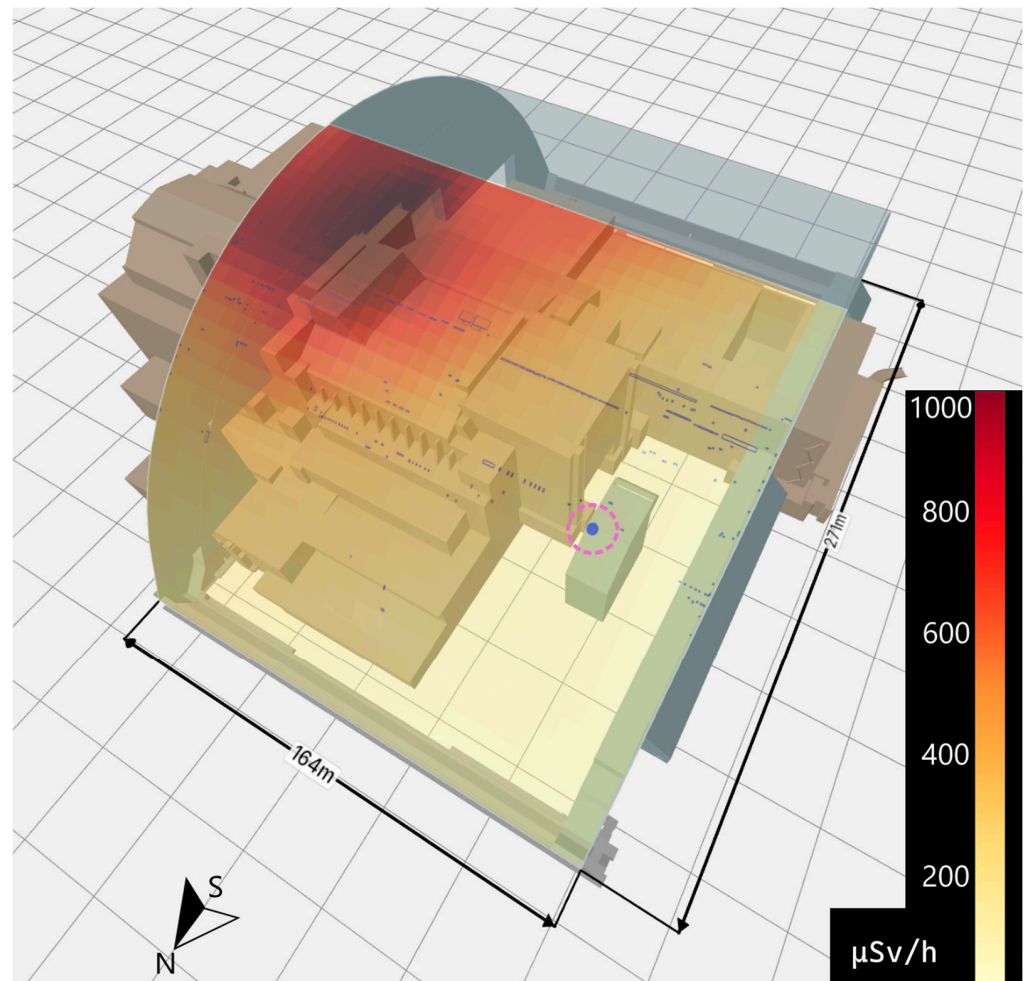


Figure 5. 3D visualisation of equivalent gamma dose rate distribution above the northern part of the NSC outer cladding. Holes in the structure are outlined in blue, while the purple dashed circle highlights the area where the cladding was damaged by the drone.

4.3. Discussion of Results and Method Limitations

The survey results made it possible to perform a primary assessment of the equivalent gamma dose rate distribution above the outer cladding of the NSC, including a detailed examination of the area surrounding the main zone of destruction. The obtained equivalent gamma dose rate distribution showed that the highly elevated gamma background above the northern part of the NSC's outer cladding is not associated with the damaged cladding areas. On the contrary, the main damage zone corresponded to relatively low equivalent gamma dose rate values, whereas the highest values were recorded over those parts of the cladding located closest to the Shelter Object.

This result is physically consistent with the structural layout of the NSC-Shelter complex. The primary blast impact occurred in the northern garage area, which is separated from the main Shelter Object space by a bioshield to protect workers. By contrast, the sections of the Arch surface located closer to the Shelter Object exhibit a much stronger gamma radiation field.

The NSC is a large-span arch structure composed primarily of a steel space-frame system with a double-layered cladding arrangement. The outer envelope consists of thin steel sheets enclosing insulation materials, separated by a ventilated interstitial space, and supported by a lattice of steel trusses. While these materials provide environmental protection and structural integrity, they are not designed to provide any substantial radiological shielding. The relatively low density and limited thickness of the cladding and insulation

layers, combined with the open, truss-based structural configuration, result in minimal attenuation of penetrating gamma radiation. Consequently, gamma emissions originating from the Shelter Object are expected to propagate through the NSC with only minor reduction, meaning that the measured radiation field above the cladding is primarily governed by the complex source distribution within the Shelter Object rather than by shielding effects of the NSC structure itself.

The data obtained were transferred to the ChNPP for further decision-making and for the planning of repair activities aimed at restoring the design characteristics of the NSC's structure. From a practical viewpoint, the survey provided not only local measurements, but also an integral spatial representation of the gamma radiation field above hard-to-access areas of the damaged outer cladding.

At the same time, the collected mapping data are far from perfect, due to the limitations associated with data collection. Firstly, the measurements were collected under real field conditions. The flights were performed in close proximity to the NSC surface and were affected by wind gusts acting on the stability of the UAV. Concurrently, due to the influence of electronic warfare systems affecting the area, it became necessary to abandon the use of a commercial DJI-type drone with advanced in-flight stabilisation in favour of a bespoke FPV UAV without sophisticated collision avoidance and automated stabilisation capability. Successful data collection relied on the skill and reflexes of a very experienced pilot. Even so, under such challenging conditions, it was not possible to ensure flights along a series of regular grid lines each maintaining a uniform height above the NSC surface. The more varied manually flown survey lines inevitably affected the quality of the subsequent data interpolation to form the resulting equivalent gamma dose rate maps.

Secondly, part of the primary dataset had to be excluded due to unreliable GPS coordinate information. This was caused both by the influence of electronic warfare systems and by the limitations of positional referencing near a large metallic structure, which both obstructed satellite visibility and introduced signal reflections. As a result, spatial referencing became one of the main sources of uncertainty affecting the final dataset.

Thirdly, the duration of the survey sessions and the total volume of collected data depended not only on the battery capacity of the UAV and associated mapping payload, but also on administrative restrictions related to flight planning and access to the approved survey zones.

The reliability of the resulting heatmap is constrained by several interacting factors, including non-uniform spatial sampling, variable stand-off distance above the NSC outer cladding, positional uncertainty under constrained GNSS conditions and possible local attenuation by structural elements. At the same time, several practical indicators support the credibility of the mapped result. The final mapped dataset consisted of 2078 retained records aggregated into 953 occupied cells of 1 m² each, with a mean of 2.18 records per occupied cell. For cells containing more than one observation, the mean ratio between the maximum and average equivalent gamma dose rate value was 1.056, indicating that the adopted maximum-based representation was conservative but remained close to the corresponding cell-average value in most multi-record cells. In addition, comparison with independent handheld measurements along a reference roof-walkway transect showed strong agreement in the overall spatial trend of the radiation field. These considerations do not replace a full formal uncertainty model, but they provide a practical basis for interpreting the resulting map as a physically credible primary operational assessment.

A formal numerical interpolation-uncertainty field was not calculated in the present study. Such an estimate would require independently quantified pointwise positional and measurement uncertainties together with a validated spatial covariance model, which were not available for the emergency survey dataset. In particular, a kriging variance would

describe uncertainty conditional on the adopted variogram model, but would not account for several major field-related uncertainty sources, including residual positional error, variable stand-off distance, detector response characteristics, irregular sampling geometry and local attenuation by structural elements. Similarly, formal error propagation through linear interpolation would require independently quantified input-error distributions.

Instead, the robustness of the resulting spatial interpretation was assessed using several complementary checks. Linear interpolation and exploratory kriging produced the same large-scale spatial trend, although only linear interpolation was used for the final equivalent gamma dose rate map. Sensitivity to cell-value representation was evaluated by comparing average-based and maximum-based values. Agreement with independent handheld measurements was quantified using Pearson correlation, MAE, RMSE, bias and range-normalised RMSE, while local sampling support was characterised through the spatial distribution and occupancy of the 1 m² cells. These checks do not replace a complete uncertainty-propagation model, but they provide a transparent and practically relevant basis for assessing the stability of the principal spatial conclusions.

Accordingly, the results obtained should be regarded as the basis for a primary assessment of the equivalent gamma dose rate above the damaged NSC outer cladding rather than as a final highly reliable high-resolution equivalent gamma dose rate map. A more detailed and robust representation of the equivalent gamma dose rate distribution would require a further increase in the number of measurements and a repeated survey with denser spatial coverage. The reported work indicates several clear directions for future development, including more advanced structured trajectory planning, improved spatial sampling control and greater use of onboard or edge-side preprocessing to support rapid field decision-making in complex nuclear emergency scenarios. In the meantime, the current data were considered sufficient to underpin planning repairs to be carried out by workers to the NSC's outer cladding.

5. Conclusions

This paper presents the results of a first UAV-based survey of the equivalent gamma dose rate above the damaged outer cladding of the New Safe Confinement structure after a UAV strike on 14 February 2025. The study demonstrates that UAV-deployed radiation measurement systems enable the rapid, operational acquisition of spatially resolved georeferenced data in areas that are otherwise inaccessible.

A primary dataset of equivalent gamma dose rate measurements was collected using the developed system and synchronised with positional data and digital photographic documentation of the damaged areas. Following data filtering based on GPS reliability and subsequent transformation into a metric coordinate framework, the dataset was processed to enable spatial analysis and mapping.

The resulting equivalent gamma dose rate distribution map revealed a pronounced spatial heterogeneity in equivalent gamma dose rate across the surveyed area. While the primary damage zone exhibited relatively low equivalent gamma dose rates, substantially elevated equivalent gamma dose rates were observed in regions adjacent to the Shelter Object. This indicates that the radiation field is governed predominantly by the influence of the Shelter Object, rather than by the damaged NSC cladding itself. From an operational perspective, the survey provided an initial characterisation of the radiation conditions above the affected sections of the NSC. These results were delivered to ChNPP to support decision-making and the planning of repair activities aimed at restoring the structure's design performance.

The findings should be interpreted in light of several methodological and environmental constraints, including wind-induced instability, electronic warfare conditions ne-

cessitating the use of FPV UAV platforms, limitations in GPS accuracy near large metallic structures and operational restrictions on flight duration and geometry. Consequently, the results herein represent a preliminary spatial assessment of equivalent gamma dose rate variation. Higher-resolution characterisation of the equivalent gamma dose rate distribution would require increased measurement density and repeated surveys with improved spatial coverage.

Author Contributions: Conceptualization, M.S. and V.S.; methodology, M.S., O.M. and V.G.; software and data curation, V.S. and M.P.; investigation, A.D., V.S., M.S. and M.P.; formal analysis and visualisation, M.S. and V.S.; writing—original draft preparation, M.S. and V.S.; writing—review and editing, T.B.S., O.M. and V.G.; supervision, M.S. and V.G.; project administration, M.S.; funding acquisition, T.B.S., M.S. and V.G. All authors have read and agreed to the published version of the manuscript.

Funding: The authors wish to acknowledge UK Research and Innovation, specifically the Engineering and Physical Sciences Research Council (EPSRC), for their funding via the Robotics and AI in Nuclear (RAIN) Project (EP/W001128/1) who have supported work in, and collaborations with Ukraine. TBS also thanks the Royal Academy of Engineering for their direct funding via the Academy Fellowships scheme. Support for this work was additionally provided through the NATO Science for Peace and Security (SPS) Programme (SPS.MYP-G5913).

Data Availability Statement: The data supporting the findings of this study may be made available from the corresponding author upon reasonable request, subject to approval and applicable restrictions. The full dataset is not publicly available, and some data cannot be disclosed due to operational, security, and site-access restrictions associated with the Chornobyl NPP site and the New Safe Confinement.

Acknowledgments: The authors would like to express their gratitude to the staff of the Chornobyl NPP, particularly S. Kondratenko, V. Shykun, S. Poplygin, and A. Evstigneev. We also thank the staff of the Institute for Safety Problems of Nuclear Power Plants of the NAS of Ukraine—specifically V. Krasnov, A. Levchenko, A. Deschenko, P. Sabenin, Yu. Rusan, Ye. Menshenin, and I. Skiter. Finally, we extend our thanks to Peter G. Martin of the University of Bristol and O. Proskurin of the Institute of Mathematical Machines and Systems Problems.

Conflicts of Interest: The authors declare no conflicts of interest.

Abbreviations

The following abbreviations are used in this manuscript:

3D	Three-dimensional
ChNPP	Chornobyl Nuclear Power Plant
EPSRC	Engineering and Physical Sciences Research Council
FPV	First-person view
GIS	Geographic information system
GNSS	Global navigation satellite system
GPS	Global positioning system
ISPNNP	Institute for Safety Problems of Nuclear Power Plants
MAE	Mean absolute error
NAS	National Academy of Sciences
NATO	North Atlantic Treaty Organisation
NFC	Near-field communication
NPP	Nuclear power plant
NRMSE	Range-normalized root mean square error
NSC	New Safe Confinement
PRD	Personal radiation detector
RAIN	Robotics and AI in Nuclear

RMSE	Root mean square error
RTK	Real-time kinematic
SPS	Science for Peace and Security
UAV	Unmanned aerial vehicle
USB	Universal serial bus

References

1. Martin, P.G.; Payton, O.D.; Fardoulis, J.S.; Richards, D.A.; Scott, T.B. The Use of Unmanned Aerial Systems for the Mapping of Legacy Uranium Mines. *J. Environ. Radioact.* **2015**, *143*, 135–140. [[CrossRef](#)] [[PubMed](#)]
2. Sanada, Y.; Torii, T. Aerial Radiation Monitoring around the Fukushima Dai-Ichi Nuclear Power Plant Using an Unmanned Helicopter. *J. Environ. Radioact.* **2015**, *139*, 294–299. [[CrossRef](#)] [[PubMed](#)]
3. Martin, P.G.; Payton, O.D.; Fardoulis, J.S.; Richards, D.A.; Yamashiki, Y.; Scott, T.B. Low Altitude Unmanned Aerial Vehicle for Characterising Remediation Effectiveness Following the FDNPP Accident. *J. Environ. Radioact.* **2016**, *151*, 58–63. [[CrossRef](#)] [[PubMed](#)]
4. Martin, P.G.; Kwong, S.; Smith, N.T.; Yamashiki, Y.; Payton, O.D.; Russell-Pavier, F.S.; Fardoulis, J.S.; Richards, D.A.; Scott, T.B. 3D Unmanned Aerial Vehicle Radiation Mapping for Assessing Contaminant Distribution and Mobility. *Int. J. Appl. Earth Obs. Geoinf.* **2016**, *52*, 12–19. [[CrossRef](#)]
5. Martin, P.; Moore, J.; Fardoulis, J.; Payton, O.; Scott, T. Radiological Assessment on Interest Areas on the Sellafield Nuclear Site via Unmanned Aerial Vehicle. *Remote Sens.* **2016**, *8*, 913. [[CrossRef](#)]
6. Zabulonov, Y.L.; Burtnyak, V.M.; Odukalets, L.A. System for Effective Remote Control and Monitoring of Radiation Situation Based on Unmanned Aerial Vehicle. *Sci. Innov.* **2017**, *13*, 40–45. [[CrossRef](#)]
7. Royo, P.; Pastor, E.; Macias, M.; Cuadrado, R.; Barrado, C.; Vargas, A. An Unmanned Aircraft System to Detect a Radiological Point Source Using RIMA Software Architecture. *Remote Sens.* **2018**, *10*, 1712. [[CrossRef](#)]
8. Briechle, S.; Sizov, A.; Tretiyak, O.; Antropov, V.; Molitor, N.; Krzystek, P. UAV-Based Detection of Unknown Radioactive Biomass Deposits in Chernobyl's Exclusion Zone. *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.* **2018**, *XLII-2*, 163–169. [[CrossRef](#)]
9. Connor, D.T.; Wood, K.; Martin, P.G.; Goren, S.; Megson-Smith, D.; Verbelen, Y.; Chyzhevskiy, I.; Kirieiev, S.; Smith, N.T.; Richardson, T.; et al. Radiological Mapping of Post-Disaster Nuclear Environments Using Fixed-Wing Unmanned Aerial Systems: A Study from Chornobyl. *Front. Robot. AI* **2020**, *6*, 149. [[CrossRef](#)] [[PubMed](#)]
10. Jońca, J.; Pawnuk, M.; Bezyk, Y.; Arsen, A.; Sówka, I. Drone-Assisted Monitoring of Atmospheric Pollution—A Comprehensive Review. *Sustainability* **2022**, *14*, 11516. [[CrossRef](#)]
11. Katreiner, H.; Kovács, B.; Horváth, Á.; Tóth, S.; Vörös, F. Cost-Effective Drone Survey of Areas with Elevated Background Radiation. *Drones* **2024**, *9*, 19. [[CrossRef](#)]
12. Le Roux, R. An Airborne Platform for Surveying Natural Radionuclides in Geological and Environmental Applications. *J. Radioanal. Nucl. Chem.* **2026**, *335*, 1615–1620. [[CrossRef](#)]
13. Chierici, A.; Malizia, A.; di Giovanni, D.; Fumian, F.; Martellucci, L.; Gaudio, P.; d'Errico, F. A Low-Cost Radiation Detection System to Monitor Radioactive Environments by Unmanned Vehicles. *Eur. Phys. J. Plus* **2021**, *136*, 314. [[CrossRef](#)]
14. Molnar, A.; Domozi, Z.; Lovas, I. Drone-Based Gamma Radiation Dose Distribution Survey with a Discrete Measurement Point Procedure. *Sensors* **2021**, *21*, 4930. [[CrossRef](#)] [[PubMed](#)]
15. Anand, R.; Harshith, K.M.B.; Raghavan, A.; Maddara, R.; Anand, P. Automated UAV to Survey and Monitor Ionising Radiation Levels in a Closed Environment. *Power Electron. Drives* **2022**, *7*, 134–145. [[CrossRef](#)]
16. Melita, C.D.; Guastella, D.C.; Cantelli, L.; Di Marco, G.; Minio, I.; Muscato, G. Low-Altitude Terrain-Following Flight Planning for Multirotors. *Drones* **2020**, *4*, 26. [[CrossRef](#)]
17. Maes, W.H. Practical Guidelines for Performing UAV Mapping Flights with Snapshot Sensors. *Remote Sens.* **2025**, *17*, 606. [[CrossRef](#)]
18. Cheng, Z.; Yang, J.; Sun, J.; Zhao, L. Trajectory Planning of Unmanned Aerial Vehicles in Complex Environments Based on Intelligent Algorithm. *Drones* **2025**, *9*, 468. [[CrossRef](#)]
19. Chi, J.; Kim, J.-I.; Lee, S.; Jeong, Y.; Kim, H.-C.; Lee, J.; Chung, C. Geometric and Radiometric Quality Assessments of UAV-Borne Multi-Sensor Systems: Can UAVs Replace Terrestrial Surveys? *Drones* **2023**, *7*, 411. [[CrossRef](#)]
20. Saveliev, M.V.; Krasnov, V.A.; Levchenko, A.P.; Novikov, A.E.; Evstigneev, A.Y.; Pantin, M.A. Measuring the Equivalent Dose Rate over the Shelter Object after Completion of the New Safe Confinement. *Nucl. Power Environ.* **2020**, *19*, 50–56. [[CrossRef](#)]

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