Research Square

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First results of radioxenon detection system in Lithuania capable to trace radioxenon release from different sources

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Abstract

Radioxenon measurement network consisting of four automated stations was deployed at the end of 2024 in Lithuania to trace radioxenon (Xe) releases from the different sources: nuclear power plants (NPPs) in neighboring countries, medical isotope production facilities (IPFs) and military or peaceful nuclear explosions (NEs). The Belarusian NPP, which operates two VVER-1200 reactors, is the closest nuclear facility. It is located just 20 kilometres from the Lithuanian border and 50 kilometres from Vilnius, the capital city. This makes it the most likely source of xenon (Xe) detections. Data of one-year Xe isotopes monitoring in Lithuanian (LT) national network revealed few episodes with several Xe isotopes detections. Episodes were analysed to identify likely release sources by evaluating the possible source region (PSR). This assessment was conducted using atmospheric transport modelling (ATM), incorporating archived HYSPLIT meteorological data for backward trajectory calculations and the JRODOS code for forward simulations. The Lithuanian network demonstrates capability to detect Xe isotopes for effective emergency response and risk mitigation purposes at national level, but also could support the Comprehensive Nuclear-Test- Ban Treaty (CTBT) with the Xe data for better source localization if needed.

1 Introduction

Radioxenon (Xe) is routinely released during reactor operation (Kalinowski & Tatlisu, 2021) at medical isotope production facilities (IPFs) (Saey, et.al., 2010) or during nuclear explosions of all purposes whether military or peaceful (Ringbom et al., 2014, Kalinowski et al, 2010). For the banning of nuclear explosions, the Comprehensive Nuclear-Test-Ban Treaty (CTBT) was established on November 19th 1996 (*The Comprehensive Nuclear-Test-Ban Treaty (CTBT)* 2025. The Treaty led to creation of the International Monitoring System (IMS) network for observation of different parameters for standard event screening, which are reported for International Data Centre (IDC). The monitoring of atmospheric concentrations of noble gases is a crucial part of the verification of the Treaty; it is done by IDC receiving daily data from the IMS network, which is then processed, analysed and made available to authorized users. National networks of radioxenon monitoring stations can serve as an additional warning system, especially to monitor background and understand the threats from nearby nuclear installations (Ringbom et al, 2023). A map of Xe producers in Europe (according to updated CTBTO web Xe map) is shown in Fig. 1 together with deployed Lithuanian (LT) Xe measurement stations network, which is also intended for early warning purposes due to exploitation of nuclear power plants (NPPs) in a close neighbourhood.

Normally reported annual releases for nuclear power plants are in the range 10^8 – 10^{11} Bq, but individual releases up to 10^{12} Bq have been observed (Ringbom, et.al., 2021),

caused for example by damaged fuel rods and/or a malfunctioning mitigation system. These releases do not pose any health issues, but serves as an indicator of irregularities in NPP performance (control rod operations, fuel failures, emergency shutdowns etc.) (Ringbom, et al., 2023, M. Kalinowski et al., 2010). However, radioxenon in the atmosphere very often is caused by releases from the medical isotope production facilities (MIPFs) (Achim, 2016). MIPFs is contributing to 95% of the global releases of the atmospheric radioactive xenon with 10^{9}-10^{13} Bq released daily (Saey, 2009). The remaining 5% are produced by NPPs, where xenon is a high-yield fission product of thermal neutron fission of ^{235}U and ^{239}Pu fission.

The Xe releases from NPPs are very well detectable within close distances. For this reason - to understand the safety of nuclear installations close to country border - the Xe monitoring systems have been deployed in Lithuania. The Belarusian nuclear power plant (NPP), located just 20 km from the Lithuanian border, as well as other planned and existing NPPs (see Fig. 1 for details), poses the most important target for monitoring xenon (Xe) releases from its operation, enabling warnings in the event of malfunctions or accidents that could impact LT.

As a part of the National Monitoring System in Lithuania the Xe monitoring network (LTX network), which employs SAUNA III and 3 SAUNA Q_B type stations (ScientaEnvinet) was installed in Lithuania at the end of 2024 under the surveillance Radiation Protection Centre (RPC) for detection of Xe composition in the atmosphere. The first SAUNA Q_B module (LTX02) have been installed on the eastern border of Lithuania, two other Q_B modules are located on the south-western (LTX03) and western (LTX04) border of Lithuania and the SAUNA III type system (LTX01) is sited in Vilnius (see magnified view in Fig. 1 for details). The Xe network serves for: monitoring of condition of the closest NPP as well as identification of other release sources. Current aim is to understand what is Xe background and what information from Xe measurements in the LTX network could be used for developing response strategies to ensure public safety in case of possible nuclear accidents at the closest NPP.

This work mostly focuses on the first one-year radioxenon air concentration measurement campaign data overview. An episode with the most prominent Xe isotopes concentration peaks have been distinguished and ATM was performed in order to identify potential radioxenon release source.

2 Xe Measurement Equipment and ATM Methods

Xenon has seven naturally occurring stable isotopes and two very-long lived isotopes, which can be considered as stable, as well as 40 unstable isotopes which undergo radioactive decay.

The four main xenon isotopes which are considered the main indicators of nuclear fission (^{133}Xe, ^{135}Xe, ^{131m}Xe and ^{133m}Xe) have sufficiently long half-lives and thus are able to be measured further away from the source days after the initial release. Due to high production efficiency and half-life of 5.24 days, ^{133}Xe is the most abundant of the four isotopes, therefore, commonly used in long-term and long-distance studies (Abdollahnejad et al., 2021). However, the detection of just this isotope is not enough to differentiate between various sources (e.g. nuclear test, civil sources, etc.). One of the reliable methods method of telling the sources apart is to determine the ratios of radioisotope concentration ratios (^{133m}Xe/^{131m}Xe and ^{133m}Xe/^{133}Xe) (Kalinowski et al., 2010). This article does not include the analysis of measured Xe isotope ratios in LT as it will be reported elsewhere. Alternatively (or in addition), the atmospheric transport modelling can be used for source localization and source term estimation.

As it was mentioned before 3 SAUNA Q_B type (Ringbom et al., 2023) (LTX02, LTX03, LTX04) and more sensitive state-of-the-art SAUNA III (Ringbom et al., 2003) (LTX01) Xe systems for automatic sampling, processing, and analysis of radioactive xenon were used in LTX network. The LTX network is similar as a five-unit Array installed in Sweden (Ringbom et al., 2023) which is operating since May 2021. Collecting the data from several stations and analysing data also by taking into account correlated Xe plumes from other known sources (STAX project) helps for better Xe source localization (Goodvin et al., 2026).

ATM methods for radioxenon source attribution can be broadly divided into: forward, backward, and inverse approaches. Forward modelling simulates the transport of radioxenon from known or assumed sources to predict concentrations at monitoring stations. It is mainly used to assess whether observed detections can be explained by known civilian emissions, such as medical isotope production facilities (Wotawa et al., 2010; Saunier et al., 2013). Backward methods trace air masses from the detection point back in time to identify potential source regions. Simple trajectory models provide rapid estimates of source direction, while more advanced backward dispersion models calculate source–receptor sensitivities, quantifying the contribution of different regions to the observed signal (Stohl et al., 1998; Seibert and Frank, 2004). Inverse modelling uses observations to estimate unknown source characteristics, including location, timing, and release magnitude. This is typically achieved by combining measurements with transport model outputs and solving an optimization problem. Bayesian approaches extend this framework by incorporating prior information and providing probabilistic estimates with uncertainty quantification (Bocquet, 2005; Saide et al., 2011).

Ensemble modelling is applied to address uncertainties in meteorological inputs and model formulations by running multiple simulations with varying parameters. This

approach provides a range of possible outcomes and improves the robustness of source attribution (Kristiansen et al., 2012; Draxler et al., 2015).

In practice, modern source attribution combines backward dispersion modelling, inverse methods and ensemble approaches, often integrating data from multiple monitoring stations to improve accuracy and reduce uncertainty (Issartel et al., 2007; Winiarek et al., 2012).

Atmospheric dispersion models (like HYSPLIT or FLEXPART) and nuclear emergency response systems (like JRODOS) can be commonly used for assessment of radiological or nuclear emergencies by simulating the movement of radionuclides, and helping trace the origin of an accident. Coupling these methods can significantly enhance nuclear accident source identification and improve preparedness efforts in Lithuania.

Currently, the HYSPLIT (Stein et al., 2016) model, combined with the ^{133}Xe concentration measurements from all four measuring stations in Lithuania, is used to produce possible source region (PSR) (Ringbom et al., 2014) for selected episodes to attribute the most probable releases source from known radioxenon sources list.

The forward dispersion of the releases from identified as the most probable candidate site is performed in order to verify the selection and obtain release rate. Forward atmospheric dispersion modelling was conducted utilizing the JRODOS 2019 (Real-time On-line Decision Support) system (Wengert, 2017) JRODOS is a well-established real-time nuclear emergency response system designed to simulate atmospheric transport, deposition, and radiological consequences following accidental releases of radionuclides. Within this framework, the LASAT (Lagrangian Simulation of Aerosol Transport) model was employed to compute the atmospheric transport and turbulent dispersion of the radioxenon plumes (Janicke & Janicke, 2007). It calculates particle trajectories based on wind fields, atmospheric stability, and boundary-layer processes, allowing reconstruction of plume evolution over regional scales.

To minimize meteorological uncertainties and enhance the accuracy of the dispersion trajectories, the modelling relied on finalized (FNL) historical weather data from NOMADS (National Operational Model Archive and Distribution System) (National Centres for Environmental Prediction, 2026). These datasets represent validated meteorological fields derived from assimilated observations and are considered more accurate than initial forecast products. The use of FNL meteorological data improves the reliability of reconstructed plume trajectories and source attribution analysis.

In the event of a significant release from any source, accurately identifying the source and predicting the dispersion of radioactive isotopes is critical for emergency response. The actions of decision makers are often based on model predictions, observations and expert

judgements. However, in our days available conventional highly sensitive radioxenon measuring systems (e.g. SAUNA or SPALAX) may not always provide rapid real-time, high-precision data needed for immediate decision-making. Therefore, it is not universal method and can act more as complementary rather than substitute system for the traditional early warning networks.

3 Results

3.1 First Xe Results from the Lithuanian Network (LTX network)

Statistics of Xe sample collection and Xe isotopes detection above minimal detection concentration (MDC) level in LTX network is presented in Table 1. Despite some failures (valves, SOV heating, membranes) and few mechanical problems with QC source movement and taking into account annual technical services – the LTX02-LTX04 systems were working in stable regime 86–95% of the time, LTX01–90% of the time from start of operation. Most of the time (39–50%) ^{133}Xe isotope is detected above MDC level, 5–10% of the time ^{131m} Xe is detected, and very rare (< 1% of the time) are other short-lived ^{133m} Xe and ^{135}Xe isotopes detected above MDC. The average MDC level for LTX02-LTX04 is on average 0.3 mBq/m^3 for ^{133}Xe, 0.2 mBq/m^3 for ^{131m} Xe and ^{133m} Xe, and 0.8 mBq/m^3 for ^{135}Xe. For LTX01 MDC level is lower (on average 0.18, 0.16, 0.13, 0.3 mBq/m^3, respectively for ^{133}Xe, ^{131m} Xe, ^{133m}Xe and ^{135}Xe). The maximal registered values of each isotope and dates of registration are shown in the Table 1. The maximal value of 428.3 mBq/m^3 of ^{133}Xe was detected in LTX01 on 10/2/2025 with all 4 isotopes detected. This event was chosen for detail analysis of Xe source reconstruction to demonstrate possible source localization technique, currently used by RPC, Lithuania.

Table 1
Summary of the data collected in the Lithuanian National Xe network

Name of Xe measurement station at place	LTX02	LTX03	LTX04	LTX01
	Adutiškis	Kybartai	Palanga	Vilnius
Constant operation since:	9/30/2024	12/20/2024	12/20/2024	12/25/2024
Number of measurements	656	540	525	1056
^{133}Xe above MDC	205	198	235	493
^{131m}Xe above MDC	26	37	34	110
^{133m}Xe above MDC	3	1	2	14
^{135}Xe above MDC	2	-	-	8
max value ^{133}Xe, mBq/m^3	323.4	20.3	14.5	428.3
date	10/2/2025	7/19/2025	10/1/2025	10/2/2025
max value ^{131m}Xe, mBq/m^3	2.9	3.1	6.1	6.1
date	10/22/2024	4/19/2025	1/28/2025	10/2/2025
max value ^{133m}Xe, mBq/m^3	11.0	0.6	0.6	17.9
date	10/2/2025	9/30/2025	10/1/2025	10/2/2025
max value ^{135}Xe, mBq/m^3	6.3	0.5 < MDC	0.6 < MDC	10.1
date	10/2/2025			10/2/2025

The time series of the ^{133}Xe, ^{131m}Xe, ^{133m}Xe and ^{135}Xe activity concentrations measured at LTX network are presented in the Fig. 2 to Fig. 5, correspondingly.

As concerning ^{133}Xe – this isotope is detected most frequently and source identification via ATM usually is performed when activity concentration of ^{133}Xe exceeded 5 mBq/m^3 or several Xe isotopes are detected. During one-year period 10 significant ^{133}Xe elevated activity episodes were registered in LT Xe network. In 2024: [1] 10.04-06, [2] 10.20, [3] 12.10 and in 2025: [4] 01.08, [5] 01.20, [6] 02.09-12, [7] 03.08, [8] 07.19, [9] 09.10, [10] 10.02. All detections were analysed using HYSPLIT and suggested most probable Xe source location direction, the results have been presented in (Plukiene et al., 2025, Maceika et al., 2025) and briefly summarized in Table 2.

Table 2
Summary of the detected elevated Xe isotopes concentrations and probable direction of Xe sources

Episode No.	Date	Xe isotopes observed and probable ATM direction
[1]	10-04-2024 10-07-2024	LTX02 ^{133}Xe max 8.6mBq/m^3, direction from north east (RU)
[2]	10-19-2024 10-23-2024	LTX02 ^{133}Xe max 13.7mBq/m^3, ^{131}Xe max 2.6mBq/m^3, direction from east (RU)
[3]	12-09-2024 12-11-2024	LTX02 ^{133}Xe max 5.8mBq/m^3, long-range transport direction from south (UA)
[4]	01-08-2025 01-09-2025	LTX01 ^{133}Xe max 2.3mBq/m^3, ^{131}Xe max 0.2mBq/m^3 LTX02 ^{133}Xe max 1.4mBq/m^3 LTX03 ^{133}Xe max 2.9mBq/m^3, ^{131}Xe max 0.5mBq/m^3 LTX04 ^{133}Xe max 2.5mBq/m^3 long-range transport direction from west Europe (BE or CZ)
[5]	01-18-2025 01-21-2025	LTX01 ^{133}Xe max 8.8mBq/m^3, ^{131}Xe max 0.7mBq/m^3 LTX02 ^{133}Xe max 5.8mBq/m^3 LTX03 ^{133}Xe max 13.8mBq/m^3, ^{131}Xe max 1.7mBq/m^3 LTX04 ^{133}Xe max 4.5mBq/m^3, ^{131}Xe max 0.9mBq/m^3 long-range transport west Europe (BE)
[11]	01-27-2025 01-28-2025	LTX04 ^{131m}Xe max 6.1mBq/m^3 long-range transport direction from west Europe (BE)
[6]	02-07-2025 02-14-2025	LTX01 ^{133}Xe max 13.2mBq/m^3 LTX02 ^{133}Xe max 24.5mBq/m^3 LTX03 ^{133}Xe max 14mBq/m^3

Episode No.	Date	Xe isotopes observed and probable ATM direction
		LTX04 ^{133}Xe max 12.6mBq/m^3 long-range transport direction from east (RU)
[12]	02-26-2025 02-27-2025	LTX03 ^{131m}Xe max 1.6mBq/m^3 LTX04 ^{131m}Xe max 2.1mBq/m^3 long-range transport direction from east (RU)
[7]	03-07-2025 03-08-2025	LTX01 ^{133}Xe max 5.9mBq/m^3, ^{131}Xe max 1.8mBq/m^3 LTX02 ^{133}Xe max 6.7mBq/m^3, ^{131}Xe max 0.9mBq/m^3 LTX03 ^{133}Xe max 12.9mBq/m^3, ^{131}Xe max 1.4mBq/m^3 long-range transport direction from west Europe (BE)
[13]	04-18-2025 04-19-2025	LTX01 ^{131m}Xe max 3.2mBq/m^3 LTX03 ^{133}Xe max 3.1mBq/m^3 LTX04 ^{133}Xe max 0.5mBq/m^3 direction from south west Europe (PL)
[14]	05-10-2025 05-12-2025	LTX01 ^{133}Xe max 1.2mBq/m^3, ^{131m}Xe max 1.6mBq/m^3 LTX02 ^{133}Xe max 1.6mBq/m^3 atmosphere transport from North (FI)
[15]	07-13-2025 07-14-2025	LTX01 ^{131m}Xe max 1.2mBq/m^3 long-range transport from south (UA)
[8]	07-18-2025 07-20-2025	LTX01 ^{133}Xe max 19.7mBq/m^3 LTX03 ^{133}Xe max 20.4mBq/m^3 LTX04 ^{133}Xe max 6.7mBq/m^3 long-range transport direction from east/south east (RU/BE)
[16]	08-14-2025 08-15-2025	LTX01 ^{133}Xe max 1.6mBq/m^3 LTX04 ^{133}Xe max 0.3mBq/m^3, ^{131m}Xe max 0.2mBq/m^3

Episode No.	Date	Xe isotopes observed and probable ATM direction
		long-range transport direction from west Europe (BE)
[9]	09-8-2025 09-12-2025	LTX01 ^{133}Xe max 8.8mBq/m^3 LTX02 ^{133}Xe max 16.3mBq/m^3 LTX03 ^{133}Xe max 4.8mBq/m^3 LTX04 ^{133}Xe max 4.5mBq/m^3 long-range transport direction from east (RU)
[17]	09-26-2025 09-27-2025	LTX01 ^{131m}Xe max 1.7mBq/m^3 transport from North (FI)
[10]	09-29-2025 10-05-2025	LTX01 ^{133}Xe max 428mBq/m^3, ^{131m}Xe max 6mBq/m^3, ^{133m}Xe max 17.9mBq/m^3, ^{135}Xe max 10mBq/m^3 LTX02 ^{133}Xe max 323mBq/m^3, ^{133m}Xe max 10.9mBq/m^3, ^{135}Xe max 6.3mBq/m^3 LTX03 ^{133}Xe max 11mBq/m^3, ^{133m}Xe max 0.5mBq/m^3 LTX04 ^{133}Xe max 11mBq/m^3, ^{133m}Xe max 0.6mBq/m^3 long-range transport direction from east (RU)

Figure 3 ^{131m}Xe activity concentrations during one-year monitoring in LTX network.

About 12 ^{131m}Xe detection episodes not exceeding activity concentrations of 10 mBq/m^3 were registered. In 2024 [2] 10.22 in 2025: [5] 01.20, [11] 02.12, [12] 02.27, [7] 03.08, [13] 04.19, [14] 05.10, [15] 07.13, [16] 08.21, [9] 09.10, [17] 09.27, [10] 10.02. Some of detections (marked in red) are same as for ^{133}Xe, but most of the, we suppose, are long-range Xe transport from West or North East direction, most probably from different IPF.

^{133m}Xe isotope activity concentration above MDC was observed at different Xe measurement stations: [4] 01/08/2025 at LTX04, [6] 2/9/2025 at LTX02, most of detections [8–10] were registered in LTX01 (7/21/2025 and 9/9/2025) and all station have detected the plume [10] on 9/29/2025-10/05/2025.

^{135}Xe isotope above MDC level was observed few times during one-year period (after removing false detections due to measurements problems QC, membrane change

procedures etc.). The red numbers indicate, that multiple Xe isotopes have been detected in these [8] and [9] plumes - as it was noted in Fig. 3.

The primary intention of the LTX network in Lithuania was to monitor Xe releases from the closest source -Belarusian NPP, however long-range transport from other distant sources (mostly from Eastern and North-Western Europe) were prevailing during one year of LTX network operation.

3.2 Atmospheric Transport Modeling

Attributing detected radioxenon to its emission source is a central challenge. For the event (episode) of the registered radioxenons concentrations spike on the 2025 10 02 the attribution of possible sources was done by applying PSR method. The obtained PSR and Ridge maps are presented in the Figs. 6.

Obtained PSR field suggest, that 2025 10 02 Xe detection can be associated release points located in the far-eastern corridor relative to LT (PSR Pearson correlation R ≅0.5). The highest correlation was obtained for the release bin at 2025-09-30 20:00:00 and the estimated released ^{133}Xe activity is about $5{\cdot}10^{13}$ Bq. It is the reasonable amount from the nuclear installations of research entities.

The forward modelling for the verification of identified potential sources was done by utilizing the JRODOS software for October 2025 elevated radioxenon activity record, with the Vilnius station showing the highest detected activity levels during the episode. The temporal evolution of the simulated plume, presented in Fig. 7, illustrates the progressive movement of the xenon cloud from eastern source regions toward Lithuania. At the earliest simulated stages (-25 h), the plume remains confined near the assumed source location with relatively high concentration gradients. Between − 20 h and − 15 h, the plume elongates along the prevailing wind direction, forming a narrow transport corridor characteristic of long-range advection. During intermediate stages (-10 h to -5 h), atmospheric mixing processes result in gradual dilution while maintaining plume directionality. At the detection time (0 h), the plume footprint intersects the Vilnius region, explaining the elevated activity levels recorded at the (LTX01) and (LTX02) monitoring station. The simulated plume dynamics therefore provide a consistent explanation for the observed station response pattern.

Forward plume dispersion modelling demonstrates substantial dilution of xenon activity during long-range atmospheric transport. The estimated dilution factors for ^{133}Xe were on the order of 10, consistent with expected atmospheric dispersion behaviour for noble gas releases transported over several hundred kilometres under synoptic-scale wind conditions.

Atmospheric transport modelling provides the essential link between measured radionuclide concentrations and their origin, enabling both source localization and source term estimation. However, source attribution is inherently complex due to atmospheric variability, sparse observations, and significant background emissions from civilian nuclear activities (Proceedings of the INMM & ESARDA 2023), therefore application of the combined methods is essential and still this is not warrantee ultimate precision.

4 Conclusions

The first year Xe isotopes monitoring in Lithuanian (LT) national network revealed dozen of episodes of elevated radioxenon concentrations, however only few ones where with several Xe isotopes detections. It makes difficult to apply straightforward radioxenon ratios method for the release source identification, however the atmospheric transport modelling is an always available alternative for the cases.

The primary intention of the SAUNA III and SAUNA Q_B network in Lithuania was to monitor Xe releases from the closest source -Belarusian NPP, however long-range transport from other distant sources (mostly from East and North-Western Europe) were prevailing. Despite usage of the PSR method, the identification and attribution of the distant release source is still a challenge, therefor usage of combined backward (PSR) as well as forward (JRODOS) atmospheric transport models is an option in order to increase credibility in the source apportionment. Therefore, the further cooperation with the other networks of radioxenon measurement systems (e.g. within EUROQUBE) and advance in application of the other tools (like FREAR) or method of isotope ratios analysis will be addressed in our future works.

Statements and Declarations

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Competing interests

The authors have no relevant financial or non-financial interests to disclose.

Author contributions

Conceptualization: Rita Plukienė, Evaldas Maceika; Methodology: Evaldas Maceika, Rita Plukienė, Aleksandras Ševčik; Formal analysis and investigation: Rita Plukienė, Evaldas Maceika, Valdemaras Milinkevičius, Dominykas Sinkevičius, Olga Chudikaitė; Writing - original draft preparation: Rita Plukienė, Evaldas Maceika, Aleksandras Ševčik; Writing - review and editing: Olga Andželika Olechnovič, Julius Žiliukas, Artūras Plukis; Supervision: Olga Andželika Olechnovič, Julius Žiliukas, Artūras Plukis.

Data availability

Data is the property of Radiation Protection Center (LT) and will be available under request.

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Figures



Figure 1

A map of Xe producers in Europe and Lithuanian Xe measurement network (adapted from CTBTO web page)

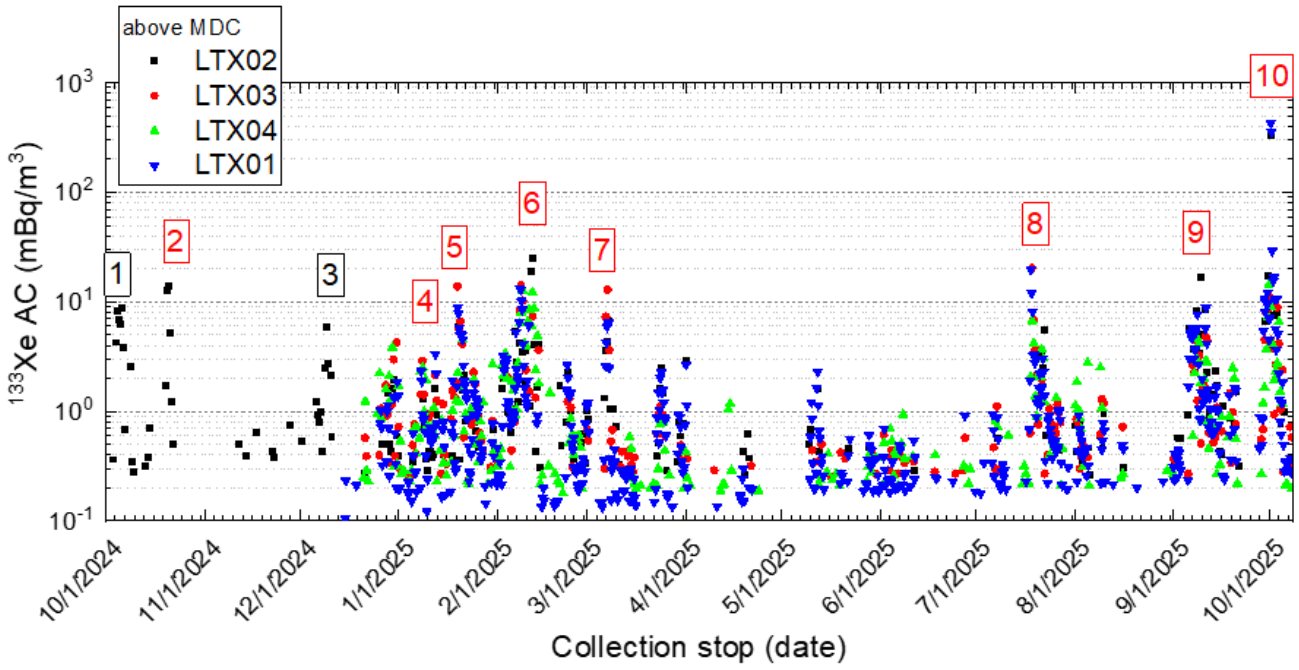


Figure 2

^{133}Xe activity concentrations during one year of monitoring LTX network. The numbers in black color indicates single ^{133}Xe detection and the red numbers – multiple Xe isotopes are detected.

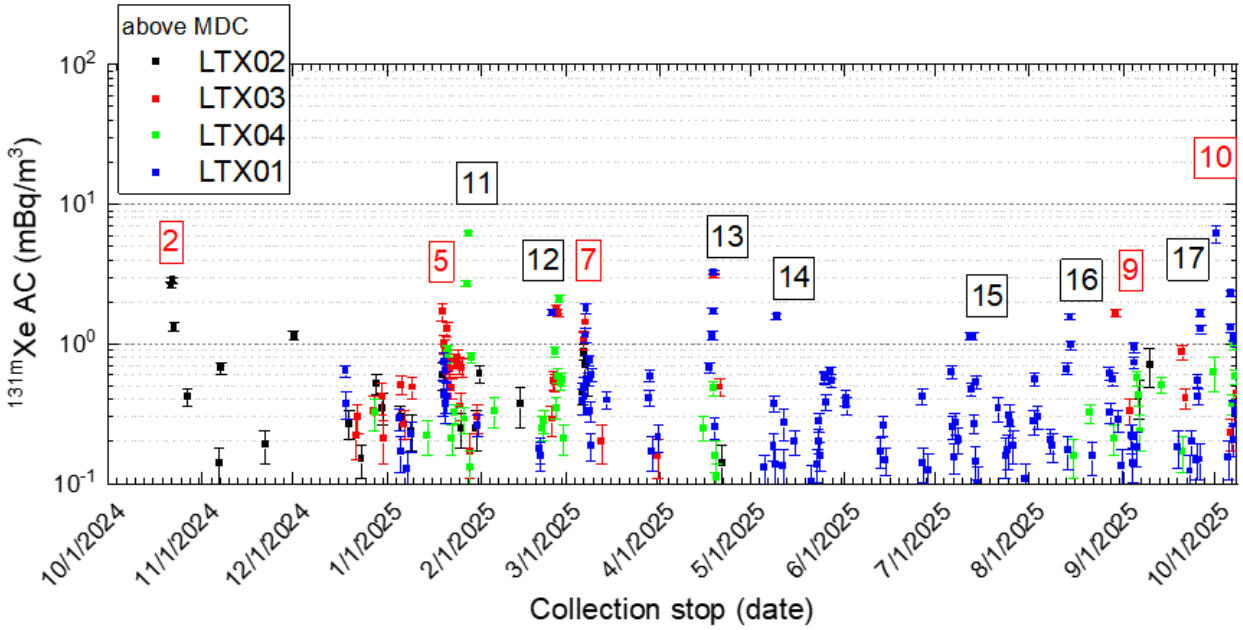


Figure 3

^{131m}Xe activity concentrations during one-year monitoring in LTX network.

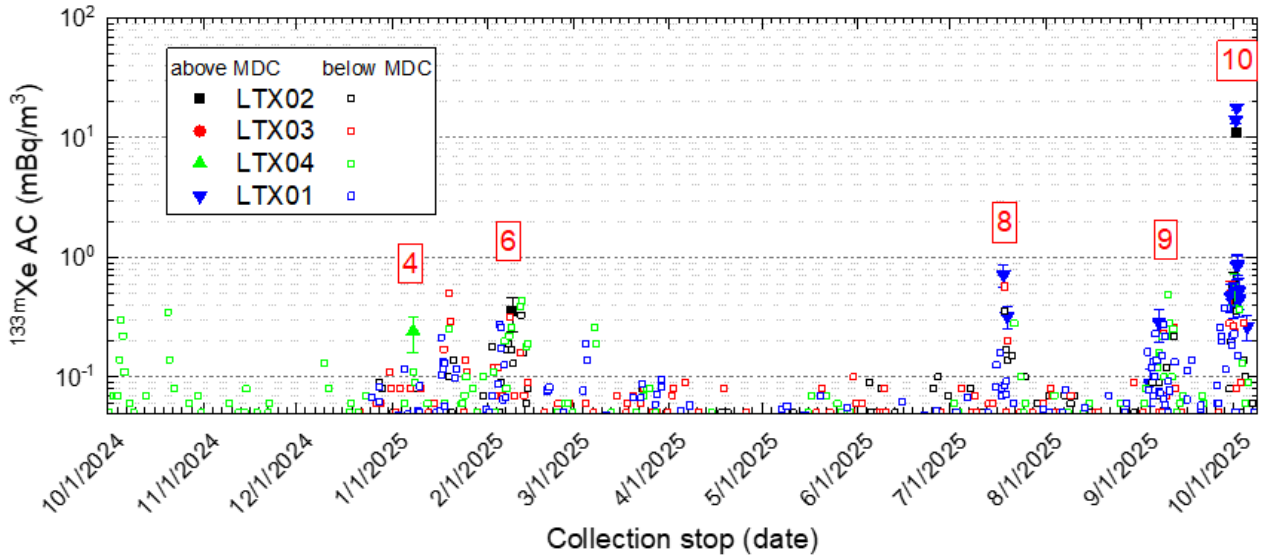


Figure 4

^{133m}Xe Activity Concentrations during one-year monitoring in LTX network.

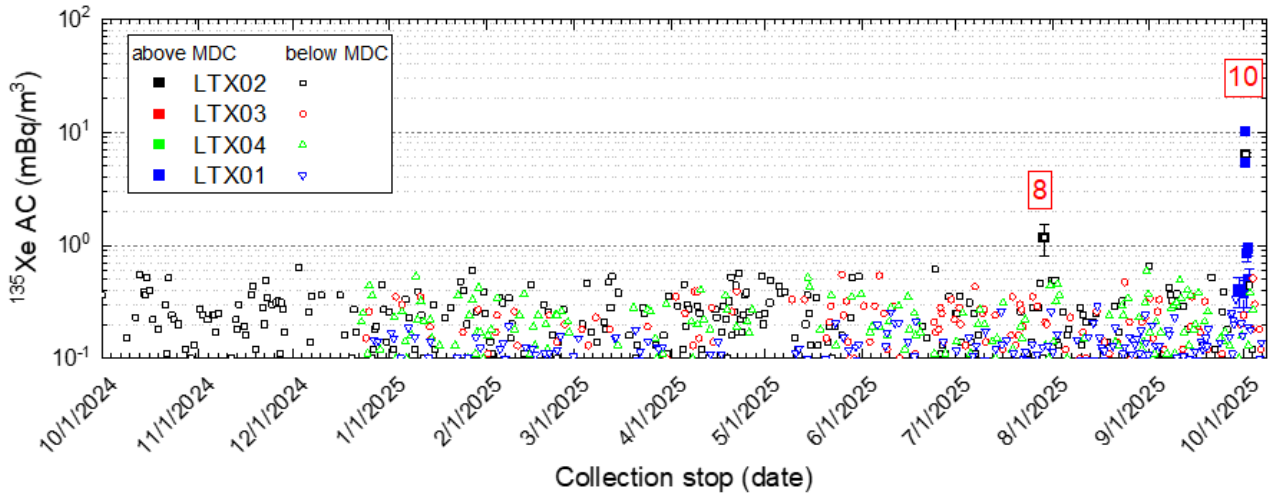


Figure 5

^{135}Xe activity concentrations during one-year monitoring in LTX network.

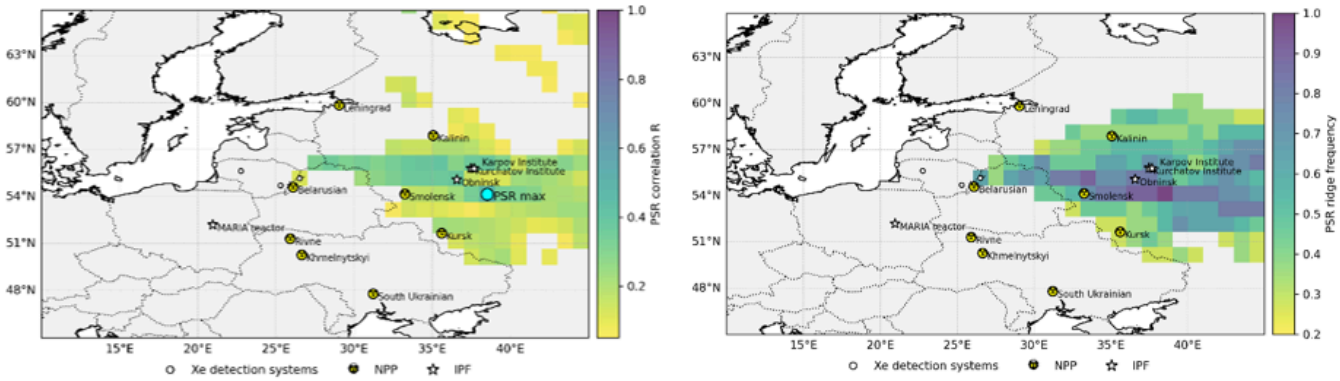


Figure 6

PSR for the 2025 10 02 detected release PSR ridge frequency (highlighting PSR) for the release time bin: 2025-09-30 20:00:00, showing the highest correlation.

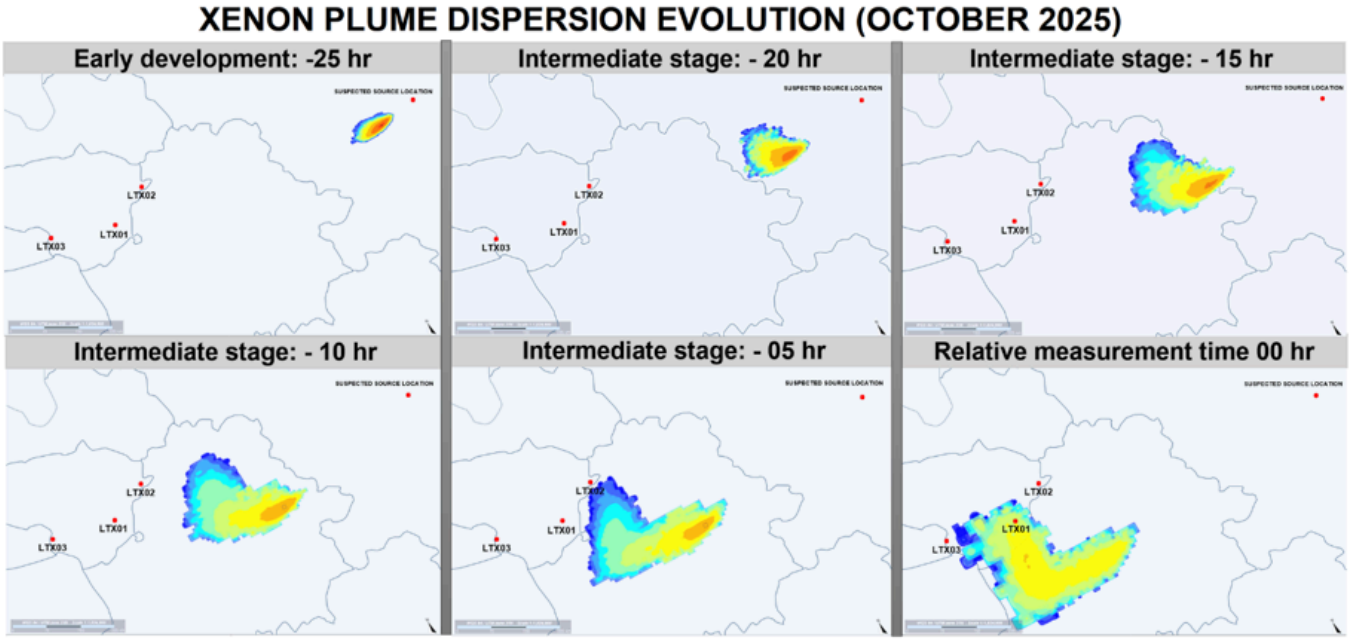


Figure 7

JRODOS assesed temporal evolution of the modeled spatial distribution prior to and at detection time. Panels show sequential stages from left to right, top to bottom: -25 h, -20 h, -15 h, -10 h, -5 h and 0 h (detection time). Colours represent relative intensity levels, with warmer colours indicating higher concentrations.