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SUPPORTING A BETTER SCREENING FOR CTBT-RELEVANT EVENTS AGAINST A RADIOXENON BACKGROUND: XEBET RESEARCH AND DEVELOPMENT

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ABSTRACT

Emissions of four radioxenon isotopes relevant for CTBT monitoring are frequently observed by the noble gas sensors of the International Monitoring System (IMS). These emissions originate from worldwide nuclear facilities, are ever-present and highly variable, and pose a challenge for global monitoring of nuclear explosions. A sophisticated approach is required for a process called screening, i.e., to distinguish for each IMS sample whether the observations can be explained by known sources or whether it possibly contains a contribution from a nuclear explosion. For this purpose, a sequence of research and development projects has been initiated, aiming to ultimately build a software tool to estimate the background radioxenon concentrations at IMS stations in an operational environment. One such currently running project, called Xenon Background Estimation Tool (XeBET), aims to deliver an aggregation of scientifically developed ideas into a software prototype. Ideas considered in XeBET are built on atmospheric transport modelling (ATM) and radionuclide statistical expertise from assessments in previous multilevel and multidisciplinary scientific investigations, specifically from three ATM Challenges to predict radioxenon concentrations and a first Screening Intercomparison Exercise to identify artificially added nuclear explosion signals. Whereas the XeBET prototype may already be used for Expert Technical Analysis once demonstrated and agreed upon after completion in 2023, its future successor project will focus on the operational implementation. This presentation discusses XeBET's context, the status of ideas and prototyping, and assesses the challenges ahead for 2023 and beyond.

INTRODUCTION

The Comprehensive Nuclear-Test-Ban Treaty (CTBT bans nuclear explosions by everyone, everywhere: above ground, under water and underground. For that, the CTBTO built a verification regime to ensure no nuclear explosion can go undetected. This verification regime consists of three components, of which one is a system of monitoring stations accommodating three waveform verification technologies (seismic, hydroacoustic, and infrasound) and one verification technology based on radionuclide detections. This state-of-the-art world-spanning network is the International Monitoring System (IMS) which has the capacity to monitor where a nuclear explosion happened and when it happened. To monitor worldwide the presence of radionuclides – aerosols and noble gases alike – the IMS currently consists of 72 certified radionuclide stations (out of a future total of 80) of which 26 are noble gas stations (out of a future total of 40). The radionuclide network is pivotal for verification since it provides additional information crucial to the 'where' and 'when' as substantiated evidence can be gained by tracing the detected radionuclides at an IMS station back to their geolocated origin. To make that happen, the International Data Centre (IDC), another component of the verification regime, operates an atmospheric transport modelling (ATM) system as the pre-eminent methodology. The IDC's ATM pipeline is maintained and gradually enhanced by state-of-the-art curated programming and operations and by utilizing high-quality weather data delivered by the European Centre for Medium-range Weather Forecast (ECMWF) and the National Centers for Environmental Protection (NCEP) in the U.S. Moreover, the advanced post-processing system Web-Grape (Web-connected Graphics Engine) makes it possible to visualize the transport and attributes of radioactive isotopes by means of dynamic maps and scientific products relevant for quick verification and CTBT-relevant analyses; see Kuśmierczyk-Michulec et al. (2023).

This presentation focusses on the radionuclide network. It briefly discusses past and present efforts for better background detection so that a more reliable screening for noble gas observations is foreseen. Attention is given to the CTBT-relevant radioisotopes Xe-133, Xe-133m, Xe-131m, and Xe-135, because these four radioxenons do not naturally occur in the environment as they originate foremost from facilities for medical isotope production (MIPFs), nuclear power plants (NPPs), and from nuclear research reactors (NRRs); see Kalinowski (2023). Since these radioxenons are emitted into the atmosphere on a daily basis at various locations on the Earth, they contribute to a highly variable yet measurable level of activity concentration (measured in mBq/m^3). This background, highest near the sources, forms a challenge for proper CTBT monitoring as it weakens the monitoring capability of the IMS; for example, when a radioxenon background detection reaches a certain critical level in an IMS sample resulting in an abnormal classification during analysis in the IDC. Also, in the rare case a nuclear test would have occurred with a weak yet still detectable signal in an IMS sample, a stronger concurrent nominal radioxenon background signal (not even abnormal) might blind the nuclear signal so that it stays unnoticed. More examples apply.

XEBET: RATIONALE

The global radioxenon background is there, poses problems, and will only grow in strength making a legitimate detection of a nuclear test signal even more challenging with the signal detection criteria and characterization schemes utilized in the IDC; see, e.g., Saey, P.R.J. et al. (2009), Bowyer, T. et al. (2013), Eslinger, P. et al., (2014), Achim, P., et al. (2016), Gueibe, C. et al. (2017), Bowyer, T.W. (2021). The current IDC procedures pertain to a three-tier qualification process for measuring signals based on a decision threshold and abnormal threshold categorization scheme: no significant signal, a nominal signal, and an abnormal signal. Note that all these signals might contain a radioxenon background signal. A suitable and wished-for approach to advance these procedures would therefore involve a quantifiable estimation of the radioxenon background on a per-sample basis in the form of a flag, that is, a binary index for a statistically significant consistency between the prediction based on known sources and the IMS measurement. The XeBET output is anticipated to be valuable for better screening – distinguishing a nuclear explosion signal from a known-source background signal.

Better characterization of detections in the IMS network, providing a more reliable event discrimination (screening), subsequently paves the way to a proper timing, location, and source strength estimation of a nuclear explosion event. For this, both radionuclide expertise and ATM expertise are required in a complementary manner. For ATM, this implies predicting a background activity concentration by simulating the transport of radioxenons from known emitters to an IMS station (or vice versa[1]). The predicted activity concentration, computed as a statistic, forms a valuable quantity for screening and source term estimation. Consequently, a statistical predicted value is to be subtracted from a concurrent IMS measurement, resulting in a non-zero and statistically significant residual.

ATM has another essential application area supporting verification methodologies and that involves addressing the yield of a nuclear detonation after detection and timing (in case screening confirmed a nuclear test). The transport of tracers by ATM provides the transported dilution of any tracer on a per tracer (xenon) basis also plays a major role. Here XeBET's sister ATM project, Source Term Estimator (STE), comes into play with the objective to estimate more efficiently and with greater certainty where a nuclear explosion event was located and what its strength was; see Kuśmierczyk-Michulec et al., (2023).

Radionuclide expertise involves isotopic ratio analyses, among other methodologies, making screening possible a priori when observations for at least two or, favourably, more radioxenons are present in a sample; see Liu, B. et al. (2023) and Kijima, Y. et al. (2023). It is, however, expected that such analyses, which involve statistical methods, might benefit from residuals in future studies, thus including ATM predictions, be it that these residuals come with an uncertainty measure. A second benefit of ATM for isotopic ratio analyses relates to sample association studies. For multiple isotope observations, checking their ratios in subsequent samples for consistency as to their radioactive decay is an approach to associate the samples with the same release. ATM simulations are then applied to gain further evidence and confidence by identifying the air masses that link distinct releases to different sets of multiple samples associated to that same release; see Kijima, Y. et al. (2022).

XEBET: CONTEXT

PAST DEVELOPMENTS

Between 2015 and 2020, the IDC participated in three international collaborations in which atmospheric transport modelling played a prominent role for a better understanding of the uncertainties involved when it comes to background predictions under different settings. The first ATM Challenge (in 2015) highlighted the use of multiple models for providing more accurate predicted concentrations in a minimal single source (MIPF) – single receptor (IMS station) scenario yet with the utilization of daily stack monitoring data for source emissions. See Eslinger et al. (2016) for a thorough account on this first ATM Challenge.

A second ATM Challenge (in 2016) was more technically demanding and highlighted the importance of high-quality meteorological fields involving more sources and IMS stations. It was first determined what the level of agreement is one can achieve between real IMS measurements and those simulated using only stack release data of Xe-133 and ATM. See Maurer et al. (2018) for an in-depth read on this second ATM Challenge.

The third Challenge, organized in 2019 was comprehensive and had a next-level scope with respect to emission inventories, simulation period, and the number of relevant samples. It

[1] ATM simulations can be performed in forward and backward mode when a so-called source-receptor sensitivity (SRS) data file is computed that covers the sensitivity between source (emitter or nuclear test) and receptor (IMS station), or vice versa, as a tracer dilution (m^{-3}). Both modes, but especially the backward mode, have their advantages and application area in analyses and for verification; see, e.g., Kuśmierczyk-Michulec et al. (2023) for a good description.

aimed at multiple meteorological input fields driving a variety of dispersion models focused on the creation of the largest possible diversity in dispersion fields starting from all credible fields and models. See Maurer et al. (2022) for an in-depth read on this third ATM Challenge.

The three progressively successful ATM Challenges gradually revealed the importance of gaining a deeper knowledge of the radioxenon background from an atmospheric transport modelling point of view. Insights and questions and newly available updated data of emission inventories (stack monitoring data) set the stage for a xenon background estimation project portfolio that commenced in 2020, initiated with funds the CTBTO received through the EU Council Decision VIII. The name XeBET (Xenon Background Estimation Tool) refers to one specific project aiming at delivering a prototype software to explore scientific ideas supporting a better xenon background estimation. The name is also used as an annotation for two precursor projects and one sister project in said portfolio. Initially, XeBET Evaluation Tool ran in 2020 and was a small project that covered a first assessment of the performance of new challenges in xenon background estimation in a multidisciplinary context. For this project, a comprehensive pre-developed test dataset plus a software evaluation program was made using these data for performance testing the various required expertise levels of ATM and radionuclide participation against a set of five metrics: detection, screening, timing, source location, and source strength. It paved the way for a follow-up project called XeBET Intercomparison Exercise, a wide-ranging trial in which newly tailored and methodically comprehensive viewpoints were to be explored not only based on ATM but also on radionuclide expertise. This Intercomparison Exercise, or "1st Nuclear Explosion Signal Screening Open Inter-Comparison Exercise 2021", was organized by Geosphere Austria (formerly known as ZAMG) and the IDC. Its objectives were 1) to identify the most suitable scientific approach of radioxenon background estimation by comparing the participants' background time series based on known sources against a provided test data set. This dataset contained simulated nuclear explosion signals added to real IMS radioxenon data, and 2) to explore new data-driven methods for characterizing the release time, location, source type and strength of a nuclear explosion event. The participants in the Exercise were given a comprehensive dataset developed during XeBET Evaluation Tool and based on synthetic explosion release scenarios, real measurements, civil source inventories, and Flexpart ATM data sets. The actual exercise test data set comprised of 23 synthetic IMS time series per hypothetical nuclear test produced by adding the actual IMS observations and hypothetical explosion signals.

The results from this extensive Intercomparison Exercise, which ended late 2022, as well as results from the three previous discussed ATM Challenges, provided a treasure trove of insights and recommendations and forms as such valuable input for current and future projects and trials involving xenon background estimation, source term estimation, ensemble prediction methodologies, high-resolution ATM, sample association, and screening.

CURRENT DEVELOPMENTS

For XeBET, it was foreseen that scientific methods from the Intercomparison Exercise were to be implemented and tested in XeBET. By collecting all residuals (for all samples) for the timeframe of the exercise (8 weeks) and applying a statistical approach (the percentile approach) to the total data, it was shown that higher quality data combined with statistical data per sample was needed to better estimate a background signal caused by known source emitters. This pertains to both the quality of emission data and the ATM predicted activity concentration, the latter coming inherently with a large uncertainty due to a coarse spatial resolution and its accompanying meteorological input. These valuable insights from the Intercomparison Exercise require XeBET to investigate methods including uncertainties by utilizing a probability density function (PDF) for both the emission signal and the ATM prediction to be combined with the normal distributed IMS observation. A PDF for an ATM prediction for each sample can be generated by running ensembles (for multiple weather inputs). However, currently produced ATM data (SRS data) do not facilitate those ensembles, whereas an Ensemble Prediction System (EPS) is foreseen in a near-future project. The prime recommendation from the Intercomparison Exercise for XeBET was related to another ATM-relevant method referring to a crude data-assimilation method called ‘nudging’, which, in a nutshell, implies using Newtonian relaxation (or repeated insertion) to correct simulated concentrations with observation data; see Groot Zwaaftink et al. (2018). Nudging is rather comprehensive to implement for the scope of XeBET. Instead, an understanding of ‘nudging’ plus a derived alternative using existing SRS data (from the 2014 dataset) combined with sensitivity analyses is anticipated.

As of 2023, the actual XeBET project is currently underway. It aims at developing a small software program in which data-driven scientific methods are to be tested. The XeBET project is short of duration with a small scope and ends 30 November 2023. The tool is a prototyping software with low technology readiness level status and explores what is feasible and required for possible future add-ons and modifications, anticipating a follow-up XeBET as an operational implementation of the radioxenon flag (a binary index for a statistically significant consistency between the prediction based on known sources and the IMS measurement) in the radionuclide pipeline of the IDC. The current project’s main objective is therefore to demonstrate that an activity concentration (mBq/m^3) can be reliably predicted on a per sample basis inside a functional software environment. To explore and test methods, a few case studies with different levels of data quality are to be defined. These case studies make use of an already existing and curated dataset, the one used in the Intercomparison Exercise. The software has three layers: a frontend layer, a functional layer, and a backend layer, built on a lean and flexible architecture which can be easily modified and enhanced by new insights and lessons learned, per layer. For a short project with the limited scope it has, this is a great advantage in the light of coping with complex data of different quality and to-be-tested scientific methods. Ultimately, it is aimed for to demonstrate one or more methods on existing data for a few relevant case studies.

XeBET’s sister project, Source Term Estimator (STE) will commence this year and nicely complements XeBET for two other important metrics (cf. the five metrics from the Intercomparison Exercise earlier), namely, localization of a nuclear explosions and an estimation of its release strength. STE is a tool that will have the potential to confirm a more confined area that could contain the source (a nuclear test) and can help estimate the probability to detect radionuclides over time; see Kuśmierczyk-Michulec (2023). Both projects feed on the Intercomparison Exercise, but where XeBET explores own methods (as explained above), it is anticipated that STE will explore machine learning algorithms to identify an anomalous observation inconsistent with previous observations and known sources, with XeBET providing input (activity concentration PDF) for STE when it comes to detection. Both projects go hand in hand and can hopefully show new functionality and innovation in scientific methods applied as such.

Next to XeBET and STE, another applied scientific effort in the IDC currently takes place in a multi-year project called ETA-RN (Expert Technical Analysis – Radionuclide) for which the event discrimination and timing metric are the main objectives and for which isotopic ratio analysis is the most suitable methodology; see Liu, B. et al. (to be published in 2023). XeBET and STE can, in that respect, very supportive to ETA-RN's objectives. It is predicted that isotopic ratio analyses might benefit greatly from a reliable ATM prediction of the background activity concentration for a given sample. Thus, a resulting PDF of ATM predicted concentrations on a per sample basis might be a valuable gauge for statistical analysis for ETA-RN for two or more isotopes and will support such analyses for a more confident event discrimination and timing calculation.

OUTLOOK

This presentation conveys a short, general overview of past and present research and development efforts concerning the radioxenon background estimation and one specific currently running project that aims to be a reliable software solution to estimate the radioxenon background for further analyses and future processing in the IDC. Together with sister project STE and IDC's own project ETA-RN, a future XeBET might provide the radionuclide pipeline of the IDC with an operational implementation of a xenon background flag plus analysis gauge.

Conclusively, on the one hand, and a non-realistic scenario at that, in a world completely devoid of the four radioxenons in question, every detection of one or more radioxenons points a priori towards a nuclear explosion event. The other extreme implies having full knowledge of the radioxenon background in space and time, by knowing all global sources of radioxenons including the temporal profile of all stack releases, the isotopic concentrations, continuous and accurate IMS measurements, and a near-perfect atmospheric transport model. Obviously, reality places us somewhere in between and with ATM, XeBET, STE, ETA-RN, and other prospect future initiatives ahead it is aimed to enhance this part of CTBT's verification technologies.

DISCLAIMER

The views expressed herein are those of the authors and do not necessarily represent the views of the CTBTO Preparatory Commission.

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