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The Potential of Radionuclide Ratios for Spectrum Categorisation Algorithms

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Why Algorithms?

To verify the Comprehensive nuclear Test Ban Treaty (CTBT) it is crucial to detect the conduct of any possible nuclear test. Therefore a monitoring system including 80 radionuclide stations all over the world is being installed, which is acquiring gigabytes of raw data every day. Most of the collected data is not of interest and only very few spectra might signify a possible nuclear test. Therefore algorithms are needed to help the human analyst to handle all the incoming data and focus on the significant spectra only.

Why Radionuclides?

Nuclear explosives use the energy released through the fission of U-235 or Pu-239. Most of these fission products are radioactive and can easily be detected.

Noble gases are chemically inert and remain gaseous. They are therefore most likely to escape even from underground nuclear explosions and remain in the atmosphere.

The xenon isotopes Xe-131m, Xe-133m, Xe-133 and Xe-135 have the best qualified fission yields and half lives: Between 9.1 hours to 11.8 days, long enough to enable reliable detection and short enough to minimise memory effects in the atmosphere.

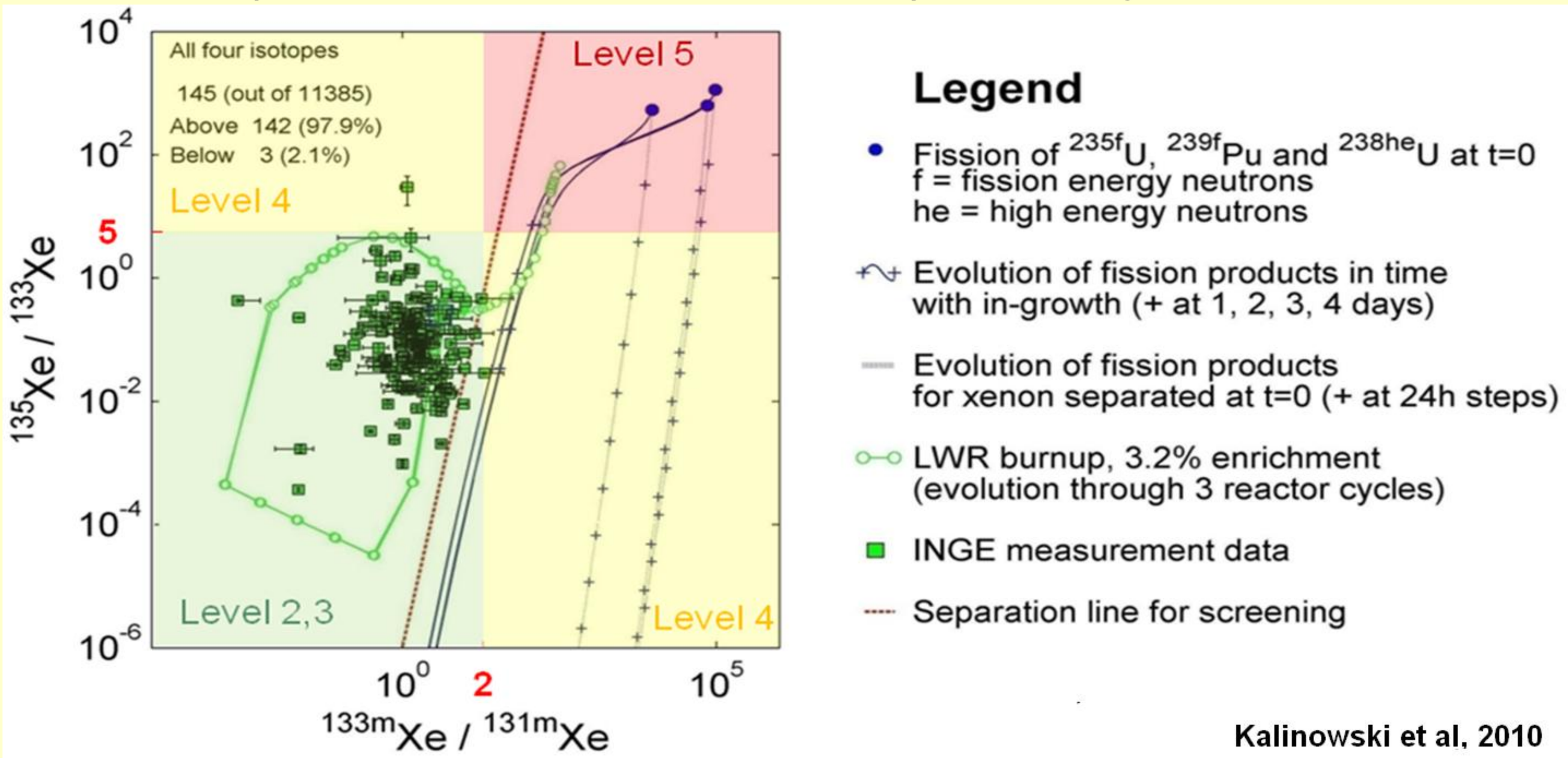
Radioactivity measurement is the most sensitive trace analysis method: Even 0.1g of Xe-133 mixed evenly in the earth's atmosphere can be detected.

Radionuclides can be used as indisputable evidence of nuclear explosions and particulary radioxenon has unique properties for nuclear explosion monitoring.

Why Radionuclide Ratios?

A major challenge for the international monitoring system is to distinguish between possible nuclear explosions and other sources. Civil sources as nuclear power plants and medical facilities release radioactivity, which can look like nuclear explosions.

Martin Kalinowski et al. have shown the possibility to discriminate between nuclear explosions and other sources by plotting the ratios of radionuclides against each other [1]. Despite its potential this technique has not been implemented yet.



Kalinowski et al, 2010

State-of-Health Criteria

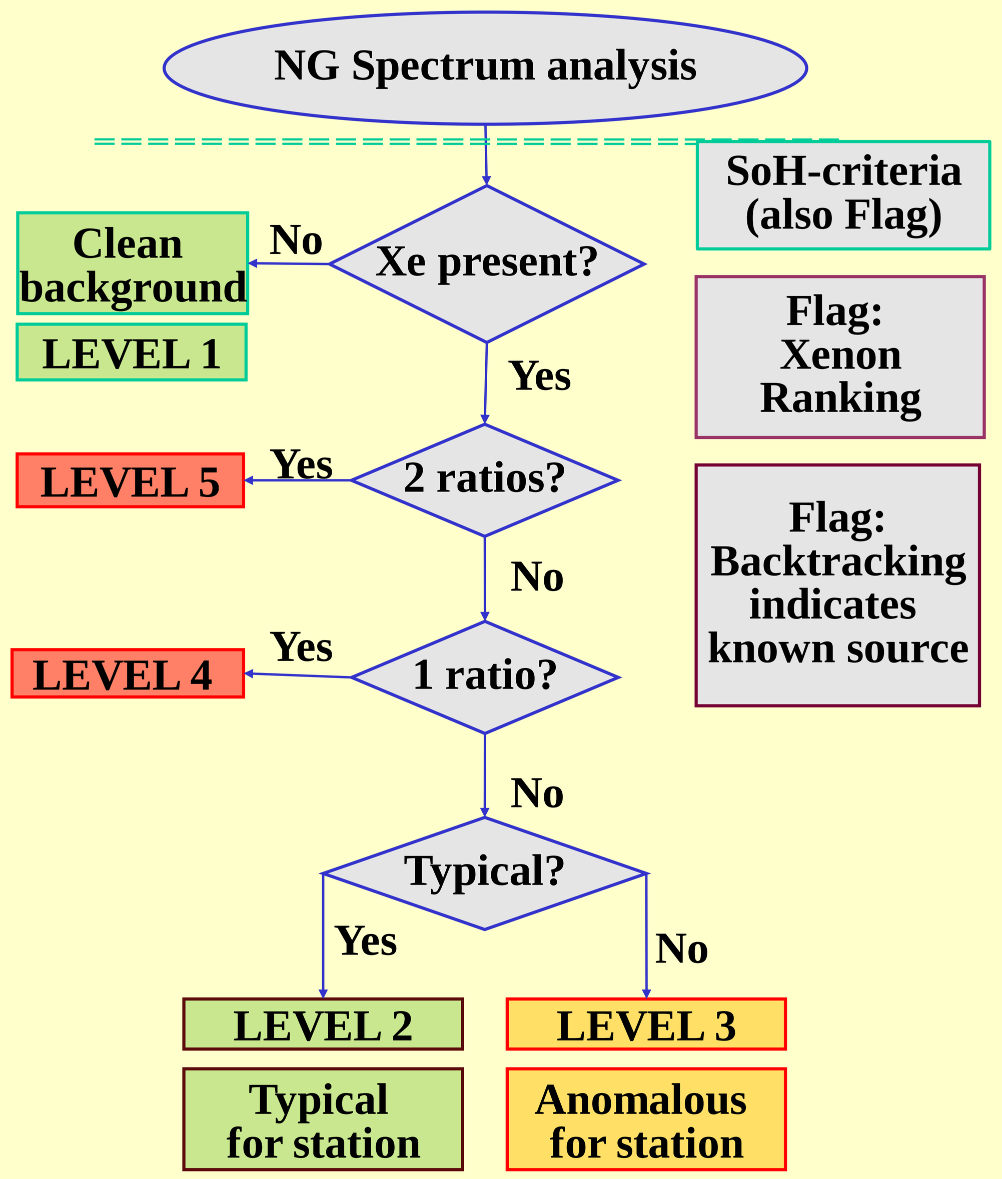
Any noble gas spectra not meeting the minimum State-of-Health criteria are marked as RED and not further regarded. To give more information on the sample reliability, all other spectra are further divided. Those only meeting the minimum standard are marked as YELLOW, those fulfilling the advanced criteria as GREEN.

The elimination of bad spectra is essential for the automatic analysis, because even single discordant values can corrupt statistical data.

SoH-criteria for SPALAX stations

Criterion					
Sampling Time	12 h	21.6 h	26.4 h	48 h	
Acquisition Time	12 h	21.6 h	26.4 h	48 h	
Xenon Volume	0.87ml				
Reporting Time	10 h			48 h	96 h
MDC-133	0.001 mBq/m³	1 mBq/m³		5 mBq/m³	
MDC-135	0.001 mBq/m³	1 mBq/m³			10 mBq/m³

Suggestion for a Spectrum Categorisation Algorithm



Having passed the minimum SoH-criteria every noble gas spectrum is searched for the presence of radioxenon. If no xenon isotope is detected, the spectrum is categorised as LEVEL1.

In case of detections the next question is, whether this activity concentration is typical for this particular station or not. Therefore the abnormal concentration is defined, using all spectra taken at this particular station in the previous year:

$$C_{abn} = Median + 3 \cdot Spread$$

If the activity concentrations of all four relevant xenon isotopes are below this limit, the spectrum is categorised as LEVEL2; is at least one value above the threshold, as LEVEL3.

In case at least one xenon isotope is present, the corresponding ratios are calculated:

$$\frac{C^{-}_{Xe\text{-}133m}}{C^{+}_{Xe\text{-}131m}} < 2 \;,\quad \frac{C^{-}_{Xe\text{-}135}}{C^{+}_{Xe\text{-}133}} < 5 \quad \text{and} \quad \frac{C^{-}_{Xe\text{-}133m}}{C^{+}_{Xe\text{-}133}} > 0.3$$

C^{+} and C^{-} are the Bayesian corrected concentrations of the corresponding isotope [2]:

$$C^{-} = C + S \cdot f^{-1}[1 - 0.975 \cdot f(C/S)]$$

$$C^{+} = C + S \cdot f^{-1}[1 - 0.025 \cdot f(C/S)]$$

Where C is the measured activity concentration, S the statistical error, calculated interactively from the station history and f(x) the cumulative Gaussian distribution function:

$$f(x) = (2\pi)^{-1/2} \int_{-\infty}^{x} e^{-\frac{z^2}{2}} dz$$

Not detected isotopes are substituted by the minimum detectable concentration as the highest possible activity concentration. Only the first two thresholds are used for the categorisation whereas the last one just serves as additional flag. If only one of the first two values is above the corresponding limit, the spectrum is categorised as LEVEL4; if both values are above the limit as LEVEL5.

In addition to these levels a number of flags is provided: Besides the SoH-Flag (Green, Yellow or Red) the Xenon Ranking gives the rank number (between 1-365) out of the up to 365 samples of the previous year. Backtracking known sources using atmospheric transport modelling may explain abnormal concentrations.

Results

In order to develop and test the spectrum categorisation algorithm presented above a Java software has been developed by Marco Verpelli.

25726 spectra were analysed, taken at more than 20 different radionuclide stations. The latter are distributed all over the world, using SAUNA, SPALAX and ARIX detectors and have low as well as medium and high background xenon concentrations.

Establishing the minimum detectable concentration for the Xenon-135 isotope as additional SoH-criterion the screening could be significantly improved and 4883 bad spectra automatically removed.

Out of the remaining 20843 spectra only 0.3% are categorised as Level 4 or 5 cases. This reduced number of samples can be easily and efficiently assessed by human analysts.

Algorithms can't substitute human analysts but they can facilitate and speed up their work and therefore help to guarantee an effective verification of the Comprehensive nuclear Test-Ban Treaty.

Total samples: 25726		Bad(SoH)	Level 1	Level 2	Level 3	Level 4	Level 5
Automatic	Total	4843	7243	12173	1366	60	1
	Percentage	-	34,80%	58,40%	6,60%	0,29%	0,01%
Reviewed	Total					1	0

Studienstiftung des deutschen Volkes

DSF Deutsche Stiftung Friedensforschung

DAAD Deutscher Akademischer Austausch Dienst German Academic Exchange Service

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References

[1] Kalinowski et al (2010), Discrimination of nuclear explosions against civilian sources based on atmospheric xenon isotopic activity ratios. In: Recent Advances in Nuclear Explosion Monitoring. Pure and Applied Geophysics Topical Volume 167/4-5. S. 517-539.

[2] M. Zähringer, G. Kirchner, Nucl. Instr. and Meth. A (2008), doi:10.1016/j.nima.2008.06.044