**Radon signals and environmental variations**

Since several decades Radon (and Thoron) in air is studied in natural environs and in dwellings. Large temporal variations are recorded consisting of periodic signals of annual and daily scale as well as non-periodic signals of mainly multi-day scale. These signal types have similarity with variations encountered in atmospheric parameters, primarily temperature and pressure. This similarity and the fact that radon is hosted in air led investigators to assume a connection between variability of radon and variation patterns of atmospheric parameters.

The general approach and assumption of atmospheric variation as drivers of radon variability turns out to be highly unclear when assessing the large accumulated sets of observations from very different scenarios. Cases interpreted to indicate positive, negative and non-correlation for the influence of P and T are abundant. Analysis of measurements relied mainly on visual inspection in the time domain, rarely in the frequency domain. Correlation diagrams (when applied) led to inconclusive patterns which certainly cannot be interpreted to prove causality. The statistical tools that were applied In these works such conclusions are assumed as there is no other frame of interpretation. Substantial evidence, especially in terms of experimental simulation is not presented. The disconformity in the raised interpretation is recognized in some of works, leading even to the statement that radon variability is “unexplainable” and therefore also useless.

The occurrence of radon (Rn-222; a radioactive noble gas) in the geological environment is investigated since the middle of the 20th century. Barbosa et al (2015; and contributions therein; Ball et al., 1991; Groves-Kirby et al., 2006; Hartman and Levy, 2005; Monin and Seidel, 1992; Toutain et al., 1999) presented an extensive overview of radon research in different scenarios – indoor, tectonic, volcanic, and as a geochemical tracer. Its behavior in the geogas (= air in the subsurface porosity) is characterized by large temporal variations that are significantly different compared to variations of: a) other trace elements in geogas (noble gases); b) variation patterns of other dynamic geophysical systems (atmospheric, tidal). Broad consensus exists that there is no simple and straightforward understanding of the phenomena and behavior of radon, and this is in spite of the relative ease of tracking radon with nuclear detectors in these environs. This lacuna in the understanding of the underlying principles hampers the development of applications – such as the prevalent suggestion to apply it as a proxy of mechanical-dynamic processes in the seismogenic and volcanic contexts.

Investigations of variation patterns of 222Rn in the geological environment applied the common practice of comparison with atmospheric parameters in the time domain or in frequency domain. Such analysis leads to ambiguities and inconclusiveness in terms of interpretation. For a review see Barbosa et al. (2015). Applying advanced analysis of the phenomena in the combined frequency-time domain (MTWF, Steinitz et al, 2007) demonstrated for the first time systematics of radon characteristics that differ extensively from those in temperature and pressure. This formed the basis for claiming that apparent similarity (in the time domain) of signal patterns of radon versus temperature and/or pressure does not substantiate causality. Applying such analysis to several radon time series originating from very different geological situations confirmed the same situation [Steinitz and Piatibratova 2010a,b; Steinitz et al. 2013a; Steinitz et al. 2015]. In a further step, the specific systematics of the periodic signals in the daily and annual frequency bands, combined with the lack of tidal gravity periodicity, led to the suggestion that a component in solar radiation is driving these signals directly.

The assumption applied in radon investigations is that the measured nuclear radiation is reflecting its concentration in the air volume sensed by the detector. This assumption relies on the existing understanding that nuclear decay is an intrinsic and random property of the radioactive isotope. The findings at the GSI on radon phenomena raise the possibility that this assumption does not fully reflect the actual situation. The proposition is that external influences are also playing a role in nuclear decay of Rn-222.

The common practice of comparison of variation patterns of 222Rn and atmospheric parameters in the time domain or in frequency domain leads to ambiguities and inconclusiveness in terms of interpretation. For a review see [3]. Applying advanced analysis of such phenomena in the combined frequency-time domain [4] demonstrated for the first time systematics of radon characteristics that differ extensively from those in temperature and pressure. This formed the basis for claiming that apparent similarity (in the time domain) of signal patterns of radon versus temperature and/or pressure does not substantiate causality. Applying such analysis to several radon time series originating from very different geological situations confirmed the same situation [5-8]. As a further step, the specific systematics of the periodic signals in the daily and annual frequency bands, combined with the lack of tidal gravity periodicity, led to the suggestion that a (direct) component in solar radiation is driving these signals.

A similar analysis approach in the frequency-time domain was applied to evaluate the time series of EXP #1 (Steinitz et al., 2011). Due to its above surface location it is influenced by large environmental variation, and therefore considered as under very unfavorable conditions. The Moving-Time-Window Fourier spectral analysis [Steinitz and Piatibratova 2007; Steinitz et al. 2011]. was applied to examine the characteristics of variation in the combined frequency-time domain. The amplitudes of the daily periodic components of the atmospheric pressure, ambient temperature and measured radon signal were derived from FFT spectra calculated per consecutive time intervals. In the case of radon (gamma,. alpha) ratios of the normalized diurnal (24-hour) versus sub-diurnal (12-hour) amplitudes align along a linear pattern, while dispersed patterns are derived for the atmospheric parameters (Figure 21 in Steinitz et al. 2011). It was argued that the dispersed patterns of the atmospheric parameters cannot generate the regular linear pattern observed for the alpha and gamma radiation signal from 222Rn and its progeny. This test was performed on the measured data using a simple statistical analysis, and its outcome is independent of other considerations and modes of analysis. As such the test is robust, and the outcome is therefore considered as an indicative criterion. The results from such examinations of data from EXP #1 do not support the notion of a direct connection between the temporal variation of the 222Rn signal and atmospheric influences, and probably negate it.

A similar analysis approach in the frequency-time domain was applied to the time series of EXP #1, which a-priory is influenced by large environmental variation, and therefore considered as under very unfavourable conditions. The Moving-Time-Window Fourier spectral analysis [4, 1] was applied to examine the characteristics of variation in the combined frequency-time domain. The amplitudes of the daily cyclic components of the atmospheric pressure, ambient temperature and measured radon signal were derived from FFT spectra calculated per consecutive time intervals. In the case of radon (gamma,. alpha) ratios of the normalized diurnal (24-hour) versus sub-diurnal (12-hour) amplitudes align along a linear pattern, while dispersed patterns are derived for the atmospheric parameters. It was argued that the dispersed patterns of the atmospheric parameters cannot generate the regular linear pattern observed for the alpha and gamma radiation signal from 222Rn and its progeny. The test was performed on the measured data using a simple statistical analysis, and its outcome is independent of other considerations and modes of analysis. As such the test is robust, and the outcome is therefore considered as an indicative criterion. As such it is much more indicative then visual examination in the time domain. The results from these investigations do not support the notion of a direct connection between the temporal variation of the 222Rn signal and atmospheric influences, and probably negate it.

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At the GSI, two modes of investigations are applied. Research of radon phenomena in geogas is performed at geological sites in southern Israel since 1990, and since 2007 laboratory simulation experiments are executed.

Field investigations are using arrays of monitoring sensors emplaced at different geological sites, at depths of in the range of 2-150 meters [Barbosa et al., 2007; Steinitz et al., 1999; Steinitz et al., 2007; Steinitz et al., 2010a, 2010b]. These arrays span a 200 km sector along the Dead Sea Transform, from the northern part of the Dead Sea to Eilat. The monitoring measurements record large radon signals in the geogas. These include periodic signals in the annual and daily periodicity bands, and non-periodic signals with wavelengths of 2-25 days. Similar combinations of such signals occur among sites of an array within a geological unit. On the other hand, among geological units different combinations occur. The similarity of the climatic conditions (arid) at the sites, excludes above surface atmospheric conditions as a cause for these differences. Furthermore, applying statistical analysis in the time, frequency and frequency-time domain using long and high-time resolution time series, demonstrates that the variation of atmospheric parameters (P, T) cannot explain the pattern of variation of radon. An evaluation of the overall characteristics of the radon signals in geogas in Israel led to raising the unconventional possibility that the periodic components (daily, annual) of the variation are linked directly to the rotational relations of the Earth-Sun system [Steinitz et al., 2007; Steinitz et al., 2010a, 2010b]. This conclusion led to suggesting that a component (unidentified) in solar radiation influences these signals – i.e. an extraterrestrial influence.

Results, obtained along similar lines, at subsurface field sites outside Israel [Steinitz et al., 2013b; Steinitz et al., 2015a] support the latter idea of an extraterrestrial influence. This serves as an indication that such influence operates at different locations on earth, at very different geologic scenarios and to a depth of hundreds of meters and even 1 km in the crust.

Experiments performed at the GSI for simulation of radon signals are the first of their kind [Steinitz et al., 2011; Steinitz et al., 2013a; Steinitz et al., 2014; Steinitz et al., 2015b]. In these experiments the Enhanced Confined Mode (ECM) is applied (see below). After initiation attainment of a stable level of nuclear radiation in such a setup is expected, reflecting a steady state between diffusion and radioactive decay. In difference with this expectation, systematic temporal variation of the radiation is observed. Large signals occur, the patterns and systematics of which are similar to those of radon signals occurring in geogas.

A key simulation is a long-term multi-sensor reference experiment, acquiring data at a resolution <1-hour. Using time series spanning 3.5 years a linkage of radon signals in geogas and in the simulation experiments is established, based on similar geophysical statistical characteristics of the signals in the time, frequency and frequency-time domains [Steinitz et al., 2011; Sturrock et al., 2012]. The outcome of the simulation experiments indicate again and probably also confirm that a component in solar radiation influences the periodic signals in radon time series.

The simulation experiments demonstrate three further unique features of the radiation from radon in air [Steinitz et al., 2013a; Steinitz et al., 2014; Steinitz et al., 2015b; Sturrock et al., 2012; Sturrock et al., 2018, Steinitz et al., 2018], which cannot be attributed to atmospheric influences and are rather interpreted to indicate an extraterrestrial influence:

1. The radiation field shows directionality (i.e. anisotropy), in difference with what is known
2. The directionality is related to global earth directions
3. Occurrence of a solar rotation periodicity (~31 days; reflecting rotation of Sun around its axis).