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SENSING AND ANALYSIS OF RADIOACTIVE RADON ^{222}Rn CONCENTRATION CHAOTIC VARIABILITY IN AN ATMOSPHERE ENVIRONMENT

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Abstract. For the first time we present the results of computational analysis and modelling the atmospheric radon ^{222}Rn concentration temporal dynamics using the data of the Chester surface observations of the Environmental Measurements Laboratory (USA Dept. of Energy). A chaotic behaviour has been discovered and in details investigated by using nonlinear methods of the chaos and dynamical systems theories. To reconstruct the corresponding strange chaotic attractor, the time delay and embedding dimension are computed. The former is determined by the methods of autocorrelation function and average mutual information, and the latter is calculated by means of correlation dimension method and algorithm of false nearest neighbours. The topological and dynamical invariants for the observed time series of the Rn concentrations are computed..

Keywords: sensing radioactive substance, atmospheric radon dynamics, chaos and dynamical systems theories

ДЕТЕКТУВАННЯ ТА АНАЛІЗ ХАОТИЧНИХ ФЛУКТУАЦІЙ КОНЦЕНТРАЦІЇ РАДІОАКТИВНОГО РАДОНУ В АТМОСФЕРНОМУ СЕРЕДОВИЩІ

О. Ю. Хецеліус, О. В. Глушков, С. М. Степаненко, А. А. Свинаренко, Ю. Я. Бунякова, В. В. Буяджи

Анотація. Ми вперше представляємо результати аналізу та моделювання часової динаміки концентрації радону в атмосфері ^{222}Rn, використовуючи дані Честер поверхневих спостережень в Environmental Measurements Laboratory (USA Dept. of Energy). Виявлені елементи хаотичної динаміки на основі застосування нелінійних методів теорій хаосу та динамічних систем. Для реконструкції відповідного дивного хаотичного аттрактору обчислені часова затримка та розмірність вкладення. Перша визначається методами функції автокореляції та середньої взаємної інформації, а остання обчислюється на основі методу кореляційного інтегралу та алгоритму помилкових найближчих сусідів. Наведені результати обчислення топологічних та динамічних інваріантів для спостережуваного часового ряду концентрацій радону.

Ключові слова: детектування радіоактивних речовин, часова динаміка атмосферного радону, теорії хаосу і динамічних систем

ДЕТЕКТИРОВАНИЕ И МОДЕЛИРОВАНИЕ ХАОТИЧЕСКИХ ФЛУКТУАЦИЙ КОНЦЕНТРАЦИИ РАДИОАКТИВНОГО РАДОНА В АТМОСФЕРНОЙ СРЕДЕ

О. Ю. Хецелиус, А. В. Глушков, С. Н. Степаненко, А. А. Свинаренко, Ю. Я. Бунякова, В. В. Буяджи

Аннотация. Мы впервые представляем результаты анализа и моделирования временной динамики концентрации радона ^{222}R в атмосфере, используя данные Честер поверхностных наблюдений Environmental Measurements Laboratory (USA Dept. of Energy). Выявлены элементы хаотической динамики на основе применения нелинейных методов теории хаоса и динамических систем. Для реконструкции соответствующего странного хаотического аттрактора вычислены временная задержка и размерность вложения. Первая определяется методами функции автокорреляции и средней взаимной информации, а последняя вычисляется на основе метода корреляционного интеграла и алгоритма ложных ближайших соседей. Приведены результаты вычисления топологических и динамических инвариантов для наблюдаемого временного ряда концентраций Rn.

Ключевые слова: детектирование радиоактивных веществ, временная динамика атмосферного радона, теории хаоса и динамических систем

1. Introduction

Sensing radioactive substances in different environments, study of their temporal and spatial dynamics and construction of the effective sensor devices is of a great importance and interest in a modern applied physics, sensor electronics etc. In the last years in many branches of science and technique principally new approaches to analysis and modelling dynamical system master parameters time series have become very popular. These new approaches are provided by using methods of an advanced non-linear analysis, a chaos, dynamical systems theories (c.f. [1-20] and Refs. therein). The matter is in the fact that many processes in the Earth and environmental sciences (physics and geophysics) are nonlinear and stochastic on their nature and their studying requires using exclusively powerful mathematical methods of nonlinear analysis and a chaos and dynamical system theories. In some our previous papers [19-24] we have given a review of new methods and algorithms to analysis of different systems of quantum physics, sensor electronics and photonics and used the nonlinear method of chaos theory and the recurrence spectra formalism to study stochastic futures and chaotic elements in dynamics of physical (namely, atomic, molecular, nuclear systems in an free state and an external electromagnetic field) systems. Moreover the nontrivial manifestations of a chaos phenomenon in some very important and interesting systems have been discovered by many authors.

The authors [3,8] have presented am effective universal complex chaos-dynamical approach to the atmospheric radon ^{222}Rn concentration fluctuations analysis, modelling and prediction from beta particles activity data of radon monitors. The topological and dynamical invariants for the time series of the atmospheric ^{222}Rn concentration in the region of the Southern Finland have been calculated using the radon concentrations measurements at SMEAR II station of the Finnish Meteorological Institute.

In this paper for the first time we present the results of computational analysis and modelling the atmospheric radon ^{222}Rn concentration temporal dynamics using the data of surface observations of the Environm. Measurement. Lab. (USA Dept. of Energy) from some sites in the United States (Chester etc). A chaotic behaviour has been discovered and in details investigated by using nonlinear methods of the chaos and dynamical systems theories [13-18]. To reconstruct the corresponding strange chaotic attractor, the time delay and embedding dimension are computed. The former is determined by the methods of autocorrelation function and average mutual information, and the latter is calculated by means of correlation dimension method and algorithm of false nearest neighbours. The topological and dynamical invariants for the observed time series of the Rn concentrations at the Chester site are computed.

2. Chaos-geometric approach to analysis and modelling radon concentration time series and input data

The time series of the atmospheric Rn concentrations extending for a least one year are available from five sites in the Unites States (Environm. Measurement. Lab., USA Dept. of Energy). The record of the radon concentrations at Chester is by far the most extensive. Measurements had been made round-the-clock 10 m above ground in a open field and data from July 1977 to November 1983 are available as continuous time series of 0.5-3 hour average concentrations (Harlee, 1978,1979; Fisenne, 1980-1985) (c.g., [2,3]. The detailed analysis of the main features for the radon data have been reviewed by Gesell and Fisenne (see [2]). The typical time series of the ^{222}Rn concentrations at Chester site (data of observations are taken from Harley,; look details in Refs. [2,3]) is presented in in Fig. 1

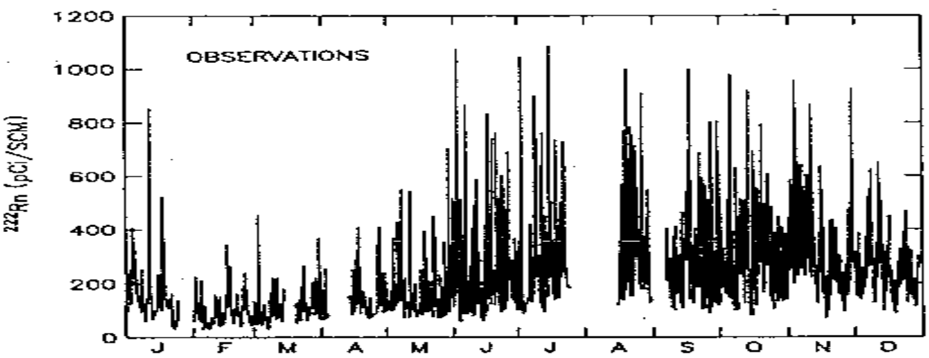

Figure 1. The typical time series of the ^{222}Rn concentrations at Chester site (data of observations) [2]).

Let us further consider the main blocks of our chaos-geometric approach, which has been presented earlier and is needed only to be reformulated regarding the problem studied in this paper. So, below we are limited only by the key moments following to Refs. [13-18].

Let us formally consider scalar measurements of the radon concentration as $s(n) = s(t_0 + n\Delta t) = s(n)$, where t_0 is the start time, Δt is the time step, and is n the number of the measurements.

Further it is necessary to reconstruct phase space using as well as possible information contained in the $s(n)$. Such a reconstruction leads to a definite set of d-dimensional vectors $\mathbf{y}(n)$ insist of initial scalar data. Further the dynamical system methods should be used. In order to reconstruct the phase space of an observed dynamical system one should apply the method of using time-delay coordinates (c.g., [13-16]).

The direct use of the lagged variables $s(n + \tau)$, where τ is some integer to be determined, results in a coordinate system in which the structure of orbits in phase space can be captured. Then using a collection of time lags to create a vector in d dimensions,

$$\mathbf{y}(n) = [s(n), s(n + \tau), s(n + 2\tau), \ldots, s(n + (d-1)\tau)],$$

the necessary required coordinates are determined. As usually, the dimension d is the embedding dimension, d_E. To determine the value of τ one should use a few methods. The first method is provided by computing the linear autocorrelation function C_L and looking for that time lag where $C_L(\delta)$ first passes through zero. The second method is provided by computing the average mutual information (look details of our version in Ref. [15]). One could remind that the autocorrelation function and average mutual information can be considered as analogues of the linear redundancy and general redundancy, respectively, which was applied in the test for nonlinearity. The general redundancies detect all dependences in the time series, while the linear redundancies are sensitive only to linear structures. Further, a possible nonlinear nature of process resulting in the vibrations amplitude level variations can be concluded.

The fundamental goal of the d_E calculation is in the further reconstruction of the Euclidean space R^d large enough so that the set of points d_A can be unfolded without ambiguity. The embedding dimension, d_E, must be greater, or at least equal, than a dimension of the corresponding chaotic attractor, d_A, i.e. $d_E > d_A$.

The correlation integral analysis is one of the widely used techniques to investigate the signatures of chaos in a time series. This method is based on using the correlation integral, $C(r)$ (c.g., [13-15]). Within this method in a case of the chaotic system the correlation exponent attains saturation with an increase in the embedding dimension. The saturation value is defined as the correlation dimension (d_2) of the attractor. The calculation of the correlation dimension can be made more exact using the method algorithm of the false nearest neighbor points.

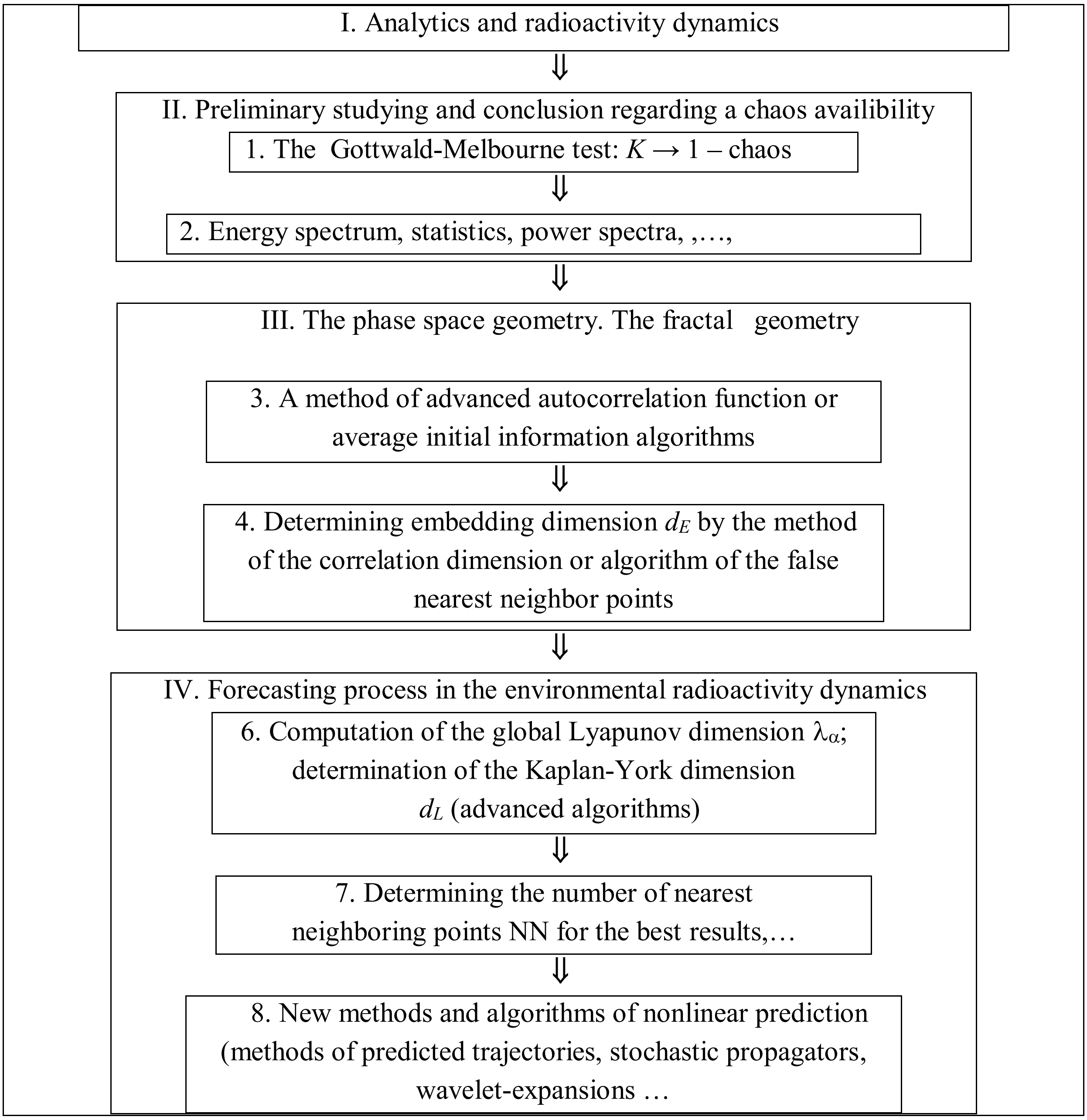

Figure 2. General scheme of the non-linear analysis, modelling and sensing algorithms to compute parameters of the radioactivity dynamics time series

The important step of the time series analysis is connected with computation of the Lyapunov's exponents. According to definition, the Lyapunov's exponents spectrum can be considered a measure of the effect of perturbing the initial conditions of a dynamical system. One should remember that in principle, the orbits of chaotic attractors are unpredictable, but there is the limited predictability of chaotic dynamical system, which is estimated by computing y the global and local Lyapunov's exponents. A negative values indicate local average rate of contraction while the positive values indicates a local average rate of expansion. Availability of numerical values of the Lyapunov's exponents allows easily to determine other invariants of the system such as the Kolmogorov entropy.

The inverse of the Kolmogorov entropy is equal to an average predictability. Estimate of the attractor's dimension is given by the Kaplan-

Yorke conjecture: $d_L = j + \frac{\sum_{\alpha=1}^{j} \lambda_\alpha}{|\lambda_{j+1}|}$ where j is such that $\sum_{\alpha=1}^{j} \lambda_\alpha > 0$ and $\sum_{\alpha=1}^{j+1} \lambda_\alpha < 0$, and the LE λ are taken in descending order. There are a few computational method to determine the Lyapunov's exponents. One of the wide spread methods is based on the Jacobi matrix of system. We have applied a method with linear fitted map (version [15]) , although the maps with higher order polynomials can be used too. Summing up above said and results of Refs. [13-22], a general scheme of an analysis, processing and forecasting any time series is presented in Figure 2.

The "prediction" block (Figure 2) includes the methods and algorithms of nonlinear prediction such as methods of predicted trajectories, stochastic propagators, neural networks modelling, renorm-analysis with blocks of the polynomial approximations, wavelet-expansions. All calculations are performed with using "Geomath" and "Quantum Chaos" PC [15-22,27-30].

3. The results and conclusions

Table 1 summarizes the results for the time lag, which is computed for first ~10^3 values of time series. The autocorrelation function crosses 0 only for the ^{222}Rn time series, whereas this statistic for other time series remains positive. The values, where the autocorrelation function first crosses 0.1, can be chosen as τ, but earlier it had been showed that an attractor cannot be adequately reconstructed for very large values of τ. So, before making up final decision we calculate the dimension of attractor for all values in Table 1. If time lags determined by average mutual information are used, then algorithm of false nearest neighbours provides d_E = 7..

Table 1.

Time lags (hours) subject to different values of C_L and first minima of average mutual information (I_{min1}) for the ^{222}Rn time series

$C_L = 0$	-
$C_L = 0.1$	258
$C_L = 0.5$	51
I_{min1}	16

Table 2 shows the results of computing a set of the dynamical and topological invariants, namely: correlation dimension (d_2), embedding dimension (d_E), two Lyapunov exponents λ_1,λ_2), Kaplan-York dimension (d_L) and average limit of predictability (Pr_{max}, hours) for the studied ^{222}Rn time series.

Table 2.

The correlation dimension (d_2), embedding dimension (d_E), first two Lyapunov's exponents, (λ_1,λ_2), Kaplan-Yorke dimension (d_L), and the Kolmogorov entropy, average limit of predictability (Pr_{max}, hours) for the 1978 ^{222}Rn time series at the Chester site

d_2	d_E	λ_1	λ_2	K_{ent}	d_L	Pr_{max}
6,03	7	0,0194	0,0086	0,028	5,88	35

Analysis of the data shows that the Kaplan-Yorke dimensions (which are also the attractor dimensions) are smaller than the dimensions obtained by the algorithm of false nearest neighbours. It is very important to pay the attention on the presence of the two (from six) positive (chaos exists!) Lyapunov's exponents λ_i. One could conclude that the system broadens in the line of two axes and converges along four axes that in the six-dimensional space. Other values of the Lyapunov's exponents $\lambda_i$are negative.

To conclude, for the first time we have presented the results of analysis and modelling the atmospheric radon ^{222}Rn concentration time series using the data of surface observations of the

Environmental Measurements Laboratory (USA Dept. of Energy) from some sites in the United States (Chester site).

We have applied such chaos and dynamical systems theories methods as autocorrelation function method and the mutual information approach, a correlation integral analysis and the false nearest neighbours algorithm, the Lyapunov exponent's analysis and surrogate data method etc. To reconstruct the corresponding strange chaotic attractor, the time delay and embedding dimension are computed. The former is determined by the methods of autocorrelation function and average mutual information, and the latter is calculated by means of correlation dimension method and algorithm of false nearest neighbours. Further, the Lyapunov's exponents spectrum, Kaplan-Yorke dimension and Kolmogorov entropy are computed. A chaotic behaviour in the atmospheric radon concentration (Chester , New Jersy) time series is firstly discovered and investigated. The Lyapunov exponent's analysis has supported this conclusion.

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Summary

Sensing radioactive substances in different environments, study of their temporal and spatial dynamics and construction of the effective sensor devices is of a great importance and interest in a modern applied physics, sensor electronics etc. In the last years in many branches of science and technique principally new approaches to analysis and modelling dynamical system master parameters time series have become very popular. The effectiveness of new approaches is provided by using methods of an advanced non-linear analysis, a chaos, dynamical systems theories For the first time we present the results of computational analysis and modelling the atmospheric radon ^{222}Rn concentration temporal dynamics using the data of surface observations of the Environmental Measurements Laboratory (USA Dept. of Energy) from the site in the United States (the Chester etc). A chaotic behaviour has been discovered and in details investigated by using nonlinear methods of the chaos and dynamical systems theories. To reconstruct the corresponding strange chaotic attractor, the time delay and embedding dimension are computed. The former is determined by the methods of autocorrelation function and average mutual information, and the latter is calculated by means of correlation dimension method and algorithm of false nearest neighbours. The topological and dynamical invariants for the observed time series of the Rn concentrations at the Chester site are computed.

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ДЕТЕКТУВАННЯ І АНАЛІЗ ХАОТИЧНИХ ФЛУКТУАЦІЙ КОНЦЕНТРАЦІЇ РАДІОАКТИВНОГО РАДОНУ В АТМОСФЕРНОМУ СЕРЕДОВИЩІ

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Реферат

Детектування радіоактивних речовин у різних середовищах, вивчення їх часової та просторової динаміки та побудова ефективних сенсорів належить до класу дуже актуальних задач сучасної прикладної фізики, сенсорної електроніки тощо. Останніми роками в багатьох галузях науки та техніки активно розвивають нові підходи до детектування радіоактивних речовин, аналізу та моделювання часових рядів їх концентрацій. Ефективність нових підходів забезпечено використанням методів вдосконаленого нелінійного аналізу, теорій хаосу та динамічних систем. У даній роботі вперше представлєно результати аналізу та моделювання часової динаміки концентрації радіоактивного радону в атмосфері, використовуючи дані поверхневих спостережень в Environmental Measurements Laboratory (USA Dept. of Energy). Виявлено елементи хаотичної динаміки на основі застосування нелінійних методів теорій хаосу та динамічних систем. Для реконструкції відповідного дивного хаотичного аттрактору обчислюють часову затримку та розмірність вкладення. Першу визначають методами функції автокореляції та середньої взаємної інформації, а останню обчислюють на основі методу кореляційного інтегралу та алгоритму помилкових найближчих сусідів. Подано результати обчислення топологічних та динамічних інваріантів для спостережуваного часового ряду концентрацій Rn.

Ключові слова: детектування радіоактивних речовин, часова динаміка атмосферного радону, теорії хаосу і динамічних систем