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Spectral Analysis Of Indoor Radon Time-Seriesusing Frequency And Time-Frequency Techniques

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ABSTRACT

A complete understanding of the dynamics governing the movement of the radon mass from soil into the indoor environment, which undoubtedly are complex and dependent on many factors, is still a matter of ongoing investigation. In the present study, we focus our attention on the study of the nature of temporal variations of indoor radon, which description must be adequately explained by any theory claiming to model the aforementioned radon-transport dynamics. A radon time-series was obtained through continuous monitoring (recorded every 10 minutes) of an indoor location using Alphaguard PQ 2000PRO. The frequency components of the time series are measured using Fourier transform (Discrete Fourier transform or DFT). Fourier analysis only reveals the containing frequencies of a signal without any time information, hence we also undertook time-frequency analysis using Short-Time Fourier Transform (STFT) as well as wavelet transform. The results reveal strong diurnal and a much weaker sub-diurnal periodicity in the temporal variation of indoor radon.

INTRODUCTION

Radon (particularly the isotope radon-222) has gained notoriety in the past few decades due to its association with elevated risks of cancer inducement, a fact attested by various reputed national and international agencies including UNSCEAR, EPA, WHO etc.[1, 2]. However, the very radioactivity of radon that is responsible for its carcinogenic nature also makes its measurement comparatively accurate and hence used as geochemical marker.

Radon is the result of a long chain of natural radioactive transmutations of the radionuclide uranium-238 found in rocks and soils. Due to its gaseous nature, it usually can easily seep into indoor environments from its origin within the earth's crust, accumulating to even harmful levels due to poor air circulation whereas in the outdoor environment it quickly dilutes to only a few $Bq.m^{-3}$[2].

The scientific and popular literature on radon is rife with reports of its carcinogenic nature, which is cited as a primary motivation for the subsequent measurements at various parts of the world. The isotopes radon-222 (simply called radon) and radon-220 (thoron) are the prime targets of study due to their longer lifetimes compared to one other naturally occurring isotope radon-219 (called actinon). Typically, measurements on radon concentration are done at an indoor location for a period of time ranging from a few hours to few months depending on the method of measurement (longer durations for passive (using SSNTDs) detectors and shorter for active detectors) and then the concentrations are compared against standard prescriptions or limits set by national and international bodies such as EPA, HPA, UNSCEAR, ICRP, WHO etc.[1-3] to conclude whether the measured radon concentration are threatening or not. Further calculations are also performed to estimate the dose on the individuals living in the studied environment, for which some simplifying assumptions are made like extending the values obtained during the measurement period to the entire year and the resulting values are again categorised as acceptable or not[4-6] .

Very short term measurements are attractive for obvious reasons but suffer the drawback of temporal fluctuations of radon which might span one or two orders of magnitude within a day, this in turn might create very significant uncertainty in the long term prediction or assessment on the effect to occupant's health. This provides a motivation to study the diurnal fluctuations of radon; also, the dynamics of the radon transport from soil or building materials to the indoor environment is still a matter of ongoing research, hindered by complex dependence on various factors, which themselves are difficult to estimate like ventilation, temperature and pressure variation in the indoor environment etc. hence any comprehensive model claiming to accurately detail the transport phenomenon of radon to indoor environment must also address the diurnal variability of radon, hence, the importance of accurately characterising the pattern. In the present work we explore three techniques of characterising the temporal time-series of indoor radon data – Fast Fourier Transform, Short-Time Fourier Transform and Wavelet Transform.

METHODOLOGY

Instrumentation and measurement

For recording of radon concentration, we used the AlphaGuard PQ 2000 Pro manufactured by Genitron Instruments, GmbH, Germany. It is based on the pulse ionisation chamber method with alpha particle spectroscopy for radon detection and has an optimal sensitivity of 1 counts per minute at 20 Bq/m^3 of radon concentration; this sensitivity is far superior to any other conventional methods[2].

The instrument was operated such that it recorded average measurements every 10 minutes to give a quasi-continuous time-series of indoor radon concentration. Measurements were carried out in an undisturbed closed room in the Department of Physics at North-Eastern Hill University, Permanent Campus, Mawlai, Shillong, India. The measurements were taken for 10 days, the duration of exposure of the instrument was constrained by its allotment for use by our group for the particular experiment. After the exposure period, the data is transferred to a computer from the instrument and converted to spreadsheet format for further analysis. All analysis were carried out using MATLAB software.

Frequency and time-frequency techniques

Fast Fourier Transform:

A time-series is a set of data whose sequential order is of importance, due to the fact that the ordering parameter in most analysis is time, however, it may well be anything else. When a signal is represented by its magnitude/value at the corresponding 'times' (either in tabular form or graphically), it is referred to as time-domain signal.

Now, Fourier theorem asserts that any periodic signal/function can be represented as a sum of simple sine waves of different frequencies and amplitudes; this opens up the possibility of expressing the signal in terms of sinusoidal amplitudes at different frequencies as opposed to the amplitudes at various 'times'; the former representation is said to be in the frequency-domain (Figure 1). The transformation of the input time-domain signal to frequency-domain is achieved via a mathematical tool called the Fourier transform for continuous signals, and for discrete datasets, a modified formulation called the Discrete Fourier Transform (DFT) is used [7]. A commonly used numerical algorithm that computes the DFT is the Fast Fourier transform (FFT), which is used in the present paper. Conversely, we can use inverse transforms to convert frequency-domain signal to time-domain signal.

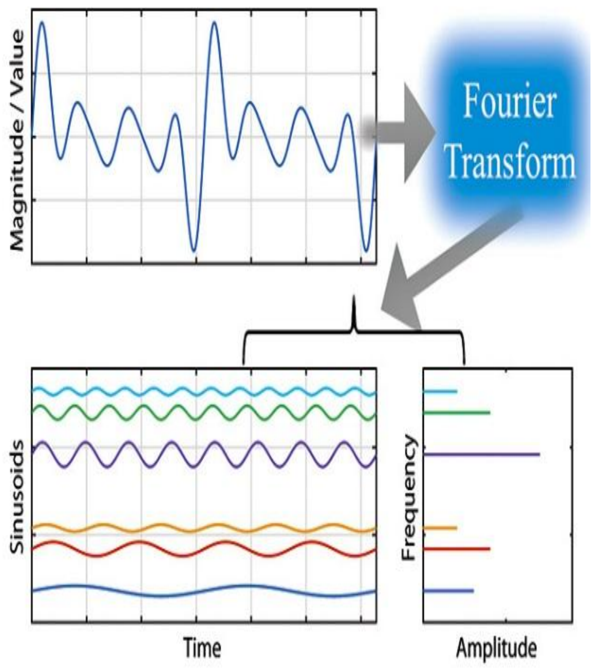

Figure 1: Basic idea on the decomposition of a signal using Fourier Transform and the information available thereby.

The Fourier transform of a signal $f(t)$ is given by the equation

$$F(\theta) = \int_{-\infty}^{\infty} f(t)e^{-2\pi i\theta t}\, dt \quad \dots (1)$$

And the DFT is given the sum

$$F(\theta) = \sum_{t=0}^{N-1} f(t)e^{-\frac{2\pi i\theta t}{N}} \quad \dots (2)$$

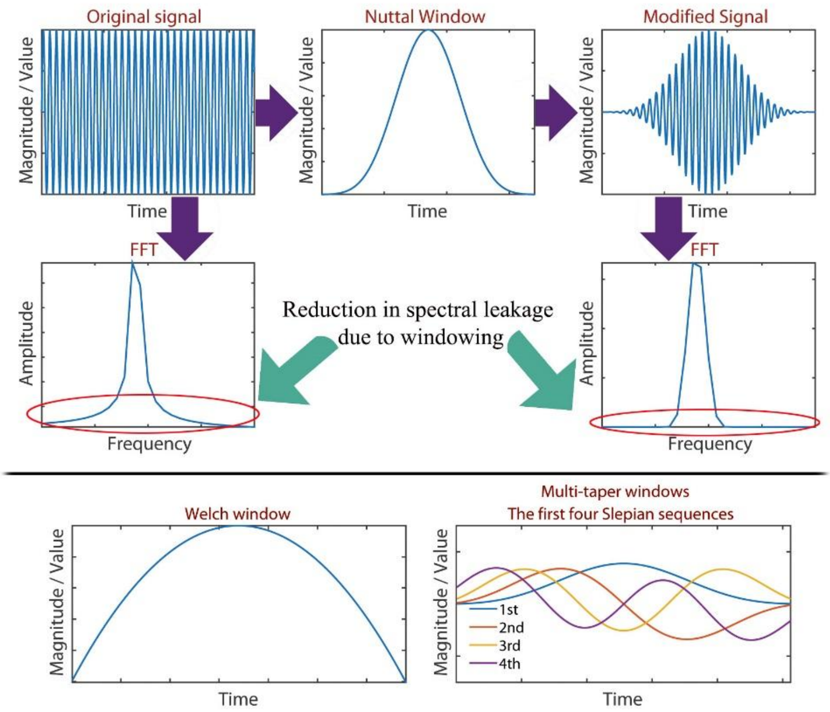

Figure 2: The usefulness of using windowing for FFT to reduce the spectral leakage; also shown are the shapes of the various windowing functions used.

where, the complex-valued function $F(\theta)$ is the result of the transform; the amplitudes of the frequencies present in the original signal are obtained from $F(\theta)$by taking its absolute value, while the phase information can be obtained from the inverse tangent of the ratio of the imaginary and real parts of $F(\theta)$; the corresponding graphs with respect θ (the frequency) are then called the amplitude spectrum and phase spectrum respectively. It is essential to remember that the variables $t, f(t)$ and θ are continuous in the original Fourier transform and discrete in DFT.

Since DFT or FFT is performed on a finite number of data points, inaccuracies creep in (like aliasing and leakage), aliasing can be reduced by using a higher sampling rate and leakage can generally be reduced by using a technique called windowing (Figure 2). In windowing, essentially the signal is multiplied by a function that smoothly decreases to zero at each end of data thus reducing the edge effects. In the present work, we have used four windows for FFT viz. Unwindowed (or rectangular), Welch, Nuttal and Multi-taper (Figure 2). The multi-taper window instead of using only one window uses a series of mutually orthogonal tapers, usually the discrete prolate spheroidal (Slepian) sequences and then averages the modified amplitude spectrums.

Short-Time Fourier Transform:

An inherent problem in the frequency domain representation is that all time-information is lost that is, no information is available on the occurrence of specific individual frequency in time. This is overcome by dividing the time signal into shorter segments of equal length and then the FFT is evaluated separately on each shorter segment, this technique is called the Short-Time Fourier Transform (STFT). The general term for the combined approach is ‘time-frequency analysis’[8]. In this case also, we can use windowing to accentuate the amplitude spectrum of the FFT.

Wavelet Transform:

The accuracy of the STFT is limited by the so-called uncertainty principle in time-frequency analysis - “For a signal, one cannot simultaneously have a sharp localization in both the time domain and frequency domain” i.e. if we identify a sharp frequency, we cannot say as sharply when in time the frequency occurs and when we try to localize frequencies in time, their sharpness decreases[8, 9]. Although all techniques are limited by the above uncertainty principle, but, the method of Wavelet Transform (WT) gives an optimum result whereas the STFT is sub-optimal in most scenarios (Figure 3)[9, 10].

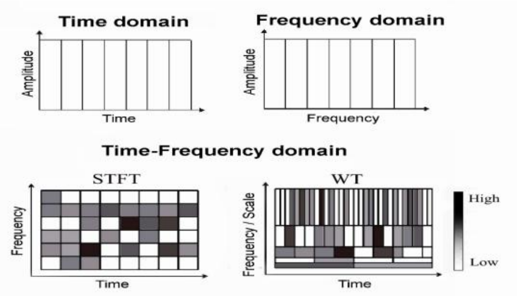

Figure 3: The information available in the three types of signal representations viz. time, frequency and time-frequency domains. The comparison of the STFT and WT clearly shows the superior utilisation of the uncertainty principle for time and frequency resolutions.

The literal meaning of a wavelet is a small wave, and in the

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current context is a wave in which oscillations decay quickly as opposed to the infinite-duration oscillations of sinusoids FT. Wavelets are a family of functions that are constructed from a single function called the 'mother wavelet' by a series of its translations and dilations:

$$\psi_{a,b}(\mathrm{t}) = \frac{1}{\sqrt{|a|}}\psi\left(\frac{t-b}{a}\right) \qquad \ldots(3)$$

$\psi_{a,b}$ are the family of wavelets, ψ is the mother wavelet, a is the scaling parameter and b is the translational parameter (Figure 4), and the wavelet transform (W_x) of the signal ($f(t)$) is obtained by the following integral

$W_x(a,b) = \int_{-\infty}^{\infty} f(t)\,\psi_{a,b}^{*}(\mathrm{t})dt \ \ldots(4)$

Where the * represent complex conjugation of $\psi_{a,b}$. Observe the similarities and differences in equations 1 and 4.

In Fourier transform, a given sinusoid has a single frequency and scaling the sinusoid in time gives a new single frequency, however, in Wavelet transform, the basis function or the mother wavelet does not have a single frequency associated with it, hence associating a frequency with scaling is not straightforward and we are forced to use the concept of pseudo-frequency; the formula for which is

$$\upsilon_p = \frac{\upsilon_c}{a\,\Delta} \qquad \ldots(4)$$

where υ_p is the pseudo-frequency, a is the scale and Δ is the sampling period and υ_c is the centre frequency of the mother wavelet taken as the frequency that maximizes its FFT amplitude or the frequency at which the highest peak in its Fourier transform is obtained.

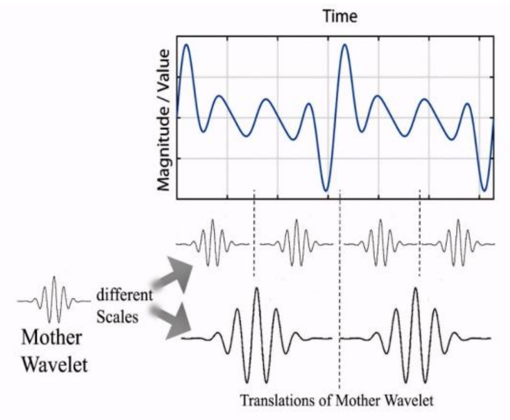

Figure 4: Basic idea on Wavelet transform, showing the stretching/scaling and translation used to derive the Wavelet coefficients.

A number of mother wavelets have been defined and it is possible to define new ones; in the present case, we have used the Morlet wavelet (Figure 5), which very closely resembles a decaying sinusoid and hence suitable for comparison with the results from FFT.

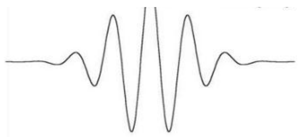

Figure 5: The Morlet Wavelet.

RESULTS

Figure 6 shows the time series (named Rn-TS). The periodicities are clearly visible in the time series itself. The FFT with different windowing functions is shown in figure 7. Diurnal and semi-diurnal (twice in one day) periodicities stand out; a bi-diurnal (once every two days) periodicity is shown by rectangular and welch windows but not by the remaining two windows. In the present work, we have preferred to use periodicity instead of frequency in the STFT as well as the WT (Figure 8 and 9) to have an easy interpretation of the result; the overlapping windows of one day duration were taken for STFT. The STFT plot (Figure 8) does not show the diurnal periodicity convincingly but semi-diurnal periodicity are detected more prominently than the FFT. A few smaller periodicities are also observable. The most visual confirmation of the diurnal periodicity is shown by WT. A few discernable semi-diurnal periodicities are also observable.

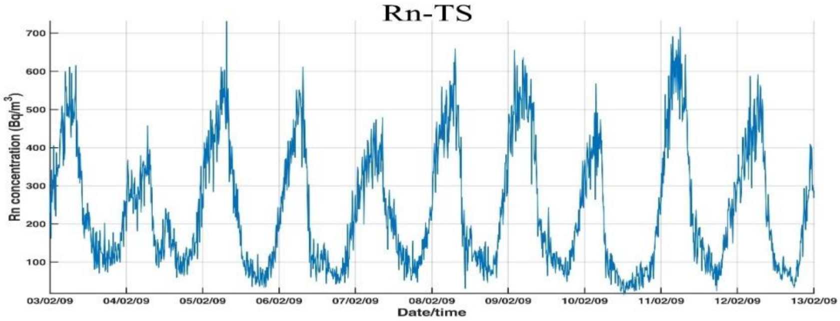

Figure 6: The indoor radon time-series, given in units of Bq/m^3 at a control room at North-Eastern Hill University campus.

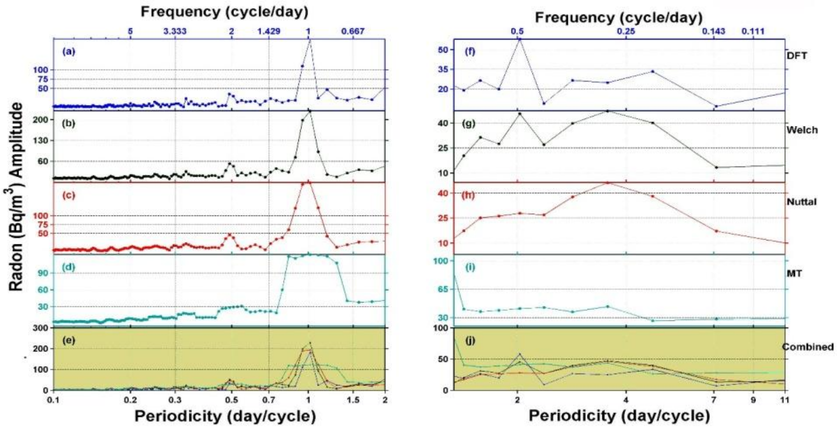

Figure 7: The FFT of the indoor radon time-series, the plot has been broken into two different frequency/periodicity parts to better highlight the peaks.

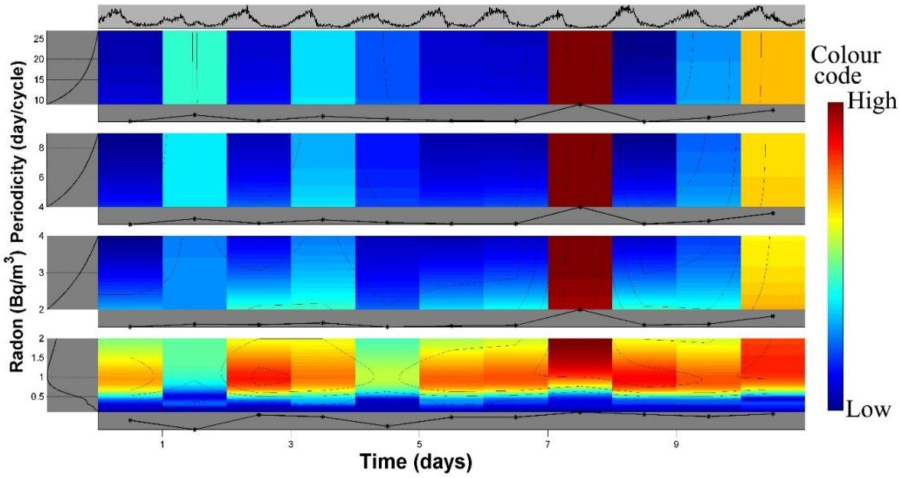

Figure 8: The STFT of the indoor radon time-series, the plot has been broken into different frequency/periodicity components to better highlight the peaks. The colour represents the amplitude of the signal at any given periodicity and time.

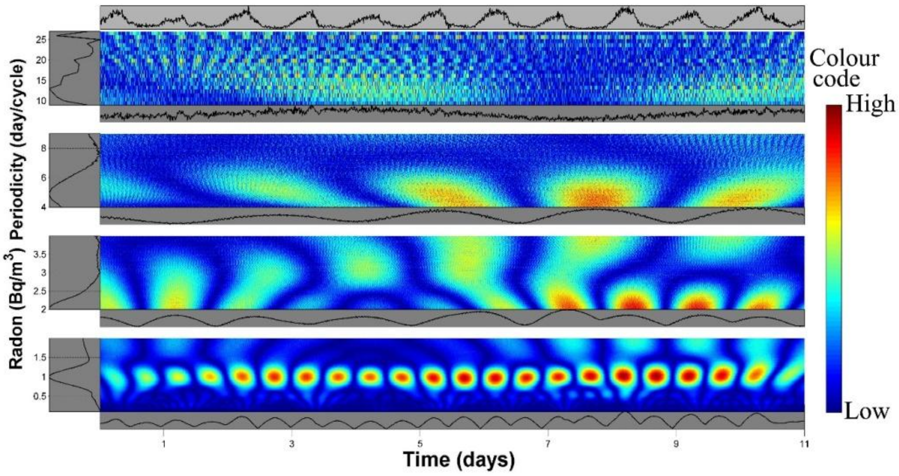

Figure 9: The WT of the indoor radon time-series, the plot has been broken into different frequency/periodicity components to better highlight the peaks. The colour represents the amplitude of the signal at any given periodicity and time.

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CONCLUSIONS

The diurnal periodicity of indoor radon concentration is established without doubt in the given dataset, from a visual inspection of the time-series itself to FFT, STFT and WT all concur to varying degrees on its occurrence.

The conflict in the resolution of the bi-diurnal periodicity within the different FFT windows (we do not expect much inference from STFT due the one-day time-window considered) and no convincing physical basis for the same as well as the small duration of the time series leads us to conclude that this is not a characteristic of the time-series, although the WT transform does show some peaks towards the later half of the time-series.

The presence of semi-diurnal periodicity are also, to a lesser degree, confirmed, however the consistency of its occurrence is doubtful. Discernable amplitude delineation are seen for the 4rd and 6th day and around the 8th day in the WT; STFT shows a slightly stronger response than the WT except for 2nd, 5th, 8th and the 10th day. Since, the dynamics of the radon accumulation in the indoor environment are not clearly known, it is difficult either to entertain or dismiss the presence of the semi-diurnal periodicity; a possible explanation may be that the amplitude of this periodicity, if it occurs, is small enough (supported by visual inspection of the time-series itself) to be obscured by the response of the radon concentration to random fluctuations in the meteorological parameters.

The sub-diurnal periodicities (larger than two times a day) are not clearly delineated throughout; the FT is inconclusive and STFT and WT do show some weakly resolved peaks at about 4 periods a day. We are hesitant to dismiss this observation as insignificant on the basis that the atmospheric pressure are shown to have such periodicities [11, 12] and considering the fact that pressure gradients are one of the driving forces for radon transport might lead to radon concentrations to follow the pressure variations.

The current analysis is just a preliminary examination into the nature of small duration variations of indoor radon concentration, hence, difficult to propose generalised conclusions. The present work should be viewed as an investigation into the various statistical tools available to further plan and analyse a more thorough and controlled set of experiments.

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