Radon time series

Bossew P.[1], Janik M.[2]

1 Retired, Vienna & Graduate School of Health Sciences, Hirosaki University, Japan

2 Radiation Measurement Research Group, QST, Chiba, Japan

v.16.9..25

17th INTERNATIONAL WORKSHOP
GARRM
(on the GEOLOGICAL ASPECTS OF RADON RISK MAPPING)
Prague, 16 – 18 September 2025

Content

1. Why measuring radon time series
2. How to measure Rn time series
3. Physical controls and proxies of the dynamic of environmental Rn
4. Examples of Rn time series
5. Radon as a tracer
6. Statistical analysis (beware some witchcraft!)

Annex: Secondary calibration of consumer-grade active Rn monitors

1) Why Rn time series?

- Radiation protection, Rn policy
- Radon as a tracer → later
- Statistical physics → later

Use in radioprotection

- Exploratory studies
  - Estimate mean Rn concentration in a room
  - Estimate means depending on usage – relevant for workplaces; to be done via time series
- Decision support
  - Estimate the probability that a reference level is exceeded, and therefore mitigation action advisable. For short-term measurements (from few days): can be done by Kovler/Tsapalov or Maringer methods.
  - Can be used to generate Rn priority maps → decision support to authorities, where protective measures should be applied.

2) How measuring Rn time series?

Monitors with active Rn detectors:

- Ionisation chamber (Alphaguard €€€, Radon Eye €)
- Semiconductor (RAD-7, -8 €€€, Radon Scout €€, Airthings €)

Sensitivity:

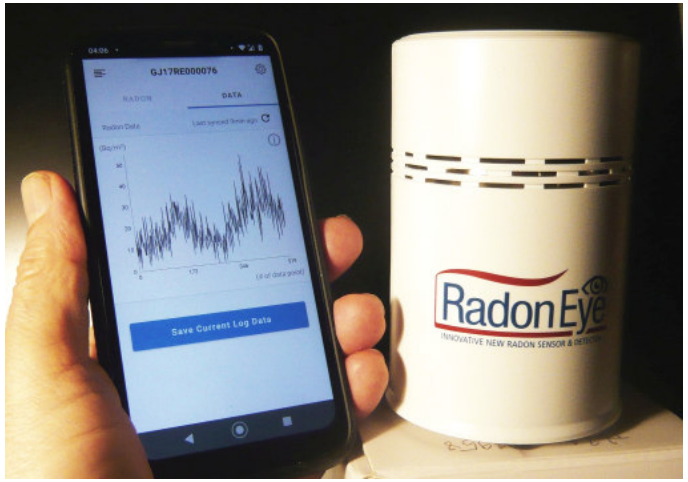
Alphaguard > RAD-8 > RAD-7, Radon Eye > Radon Scout > Airthings

Measurement intervals:

- High sensitive detectors: 10 min
- Middle (e.g. Radon Eye): 1 h
- Low: 1 d

Some can discriminate between Rn and Tn

Alphaguard



Radon Eye

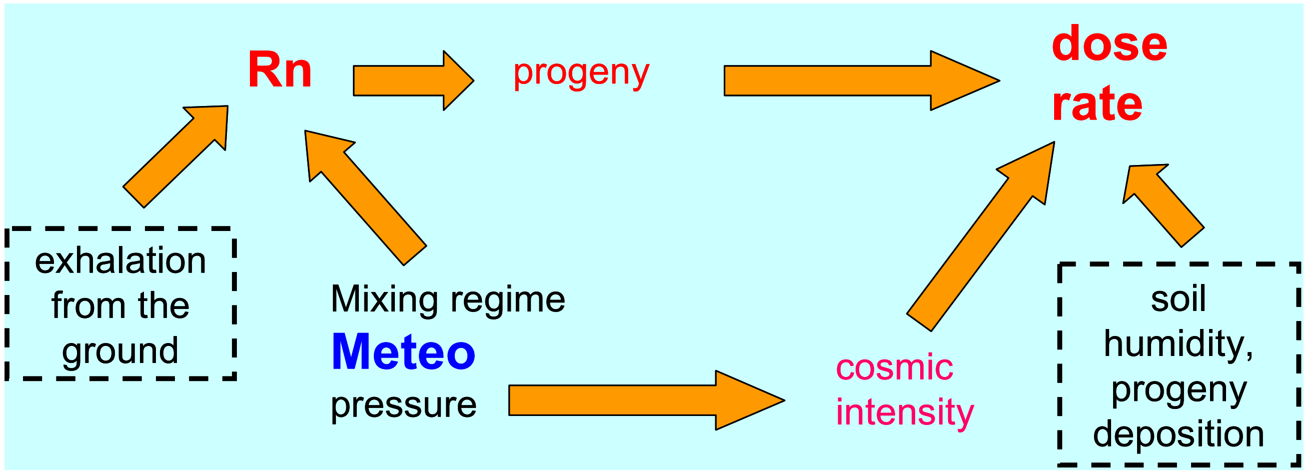
RAD-8

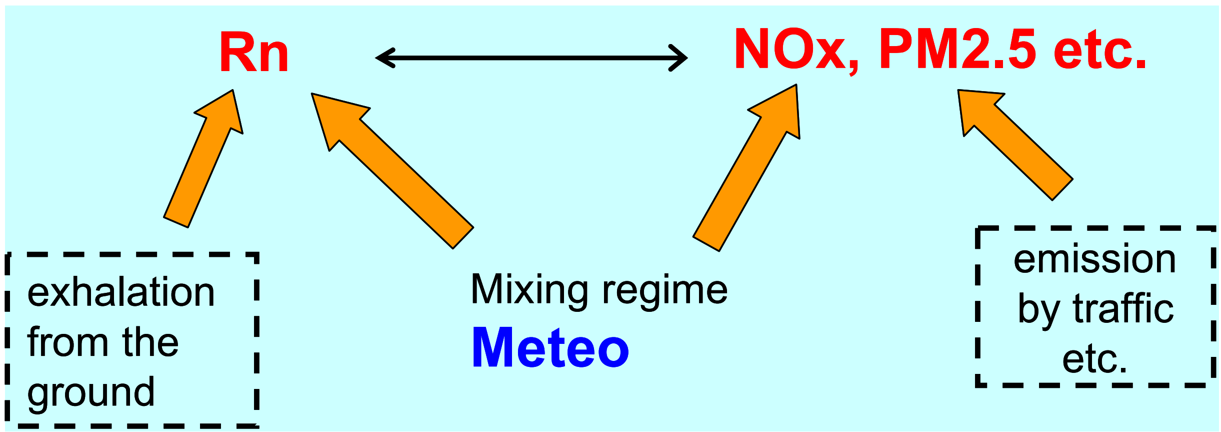
RAD-7

Radon Scout

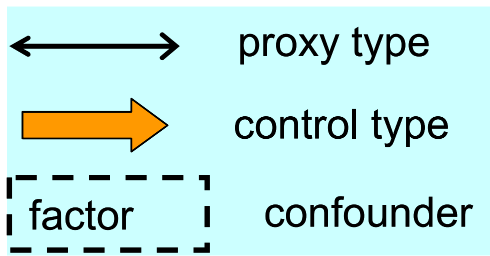
Airthings
Corentium Home 2

3) Physical controls and proxies





control and proxy type association, on the examples on association between Rn and dose rate and Rn and air pollution.
Mixing regime: atmospheric turbulence, mixing layer height



control vs. proxy

We call a variable Y control or predictor of X if there is a physical causal influence of Y on X;

we call X_1 and X_2 proxies if there is no causal influence of one on the other, but both are (partly) causally influenced by a common Y; therefore there is a statistical association between X_1 and X_2.

Other influences on Y, X or X_1 and X_2 are called confounders. These “blur” or “obscure” the statistical associations X~Y or X_1~X_2.

Causal control can be delayed due to the inertia of a system. This makes it more difficult to detect a relation.

The terminology proposed here is not authoritative! Sometimes the terms are used interchangeably.

- The mixing regime denotes the condition which enables establishing a certain atmospheric (Rn or other pollutant) concentration.
- It depends on vertical turbulent and advective transport, itself depending on air buoyancy by solar heating, wind induced mixing and the height of the atmospheric mixing layer (also: planetary boundary layer), which acts as a kind of lid on the lower troposphere.
- Usually its height is between some 100 m and several km above ground. The more “space” is available for a pollutant through higher mixing layer height and the more turbulent mixing, the lower is the concentration.
- The mixing layer height usually has distinct diurnal and seasonal cycles + aperiodic synoptic characteristic

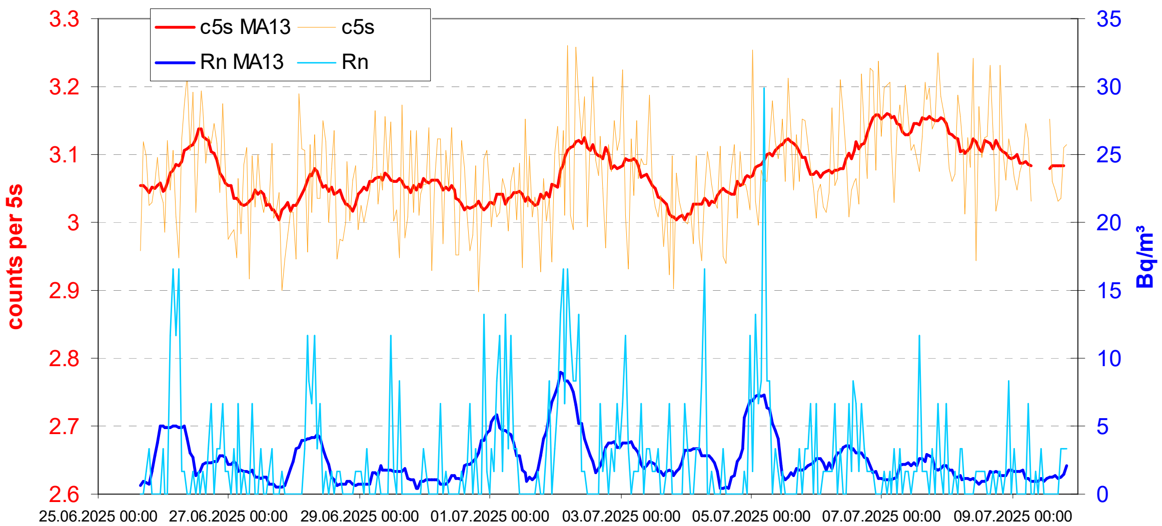
From physics one would expect a relation between **Rn concentration and ambient dose rate** (DR):

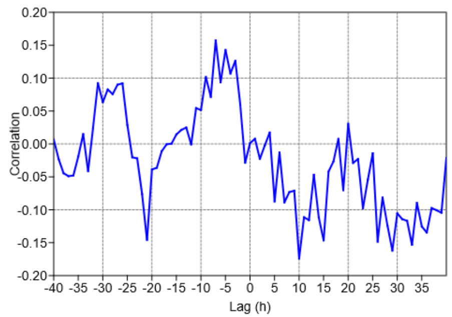
(1) Rn progeny are gamma emitters and

(2) Rn and DR are controlled by common predictors, namely meteorological variables, in particular mixing regime and air pressure.

Hence Rn is (1) a control of DR, at the same time they are proxies through (2). A 2-week 2-week experiment: performed with a RadonEye, simultaneously operated with a CzechRad G-M counter based DR monitor].

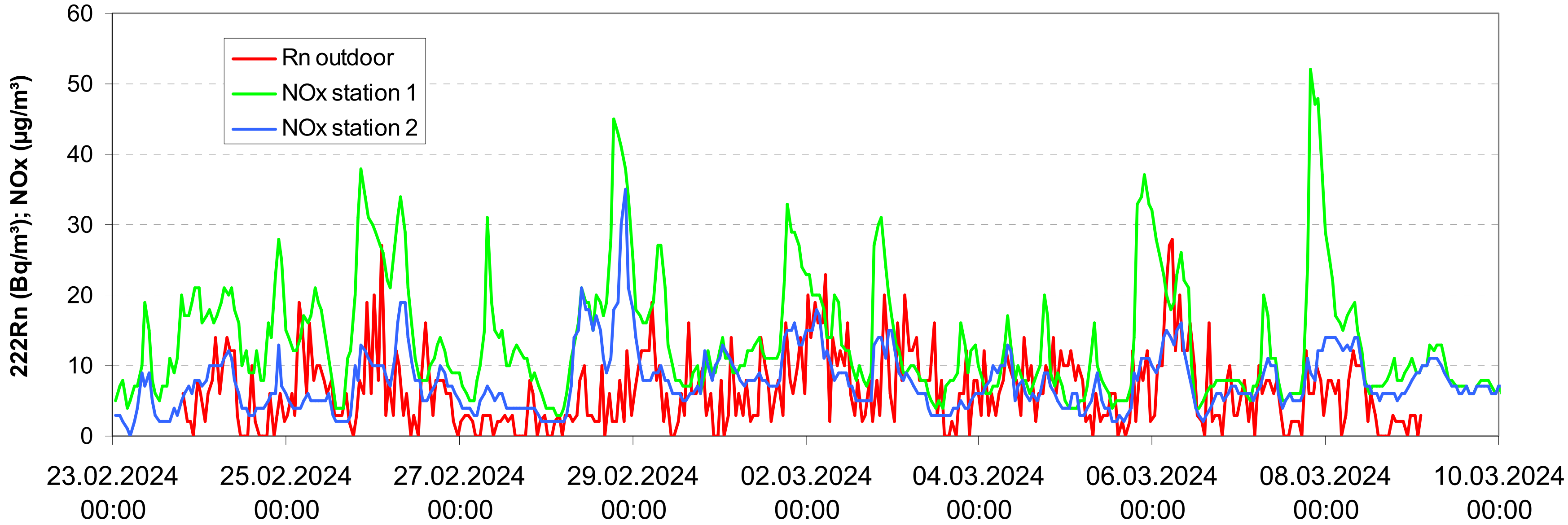
Correlation is weak because of various disturbing influences, but one can notice a certain degree of association. Cross-correlation analysis shows that DR follows Rn with about 7 hours delay with Pearson r= 0.15, highly significant with p=0.0047.





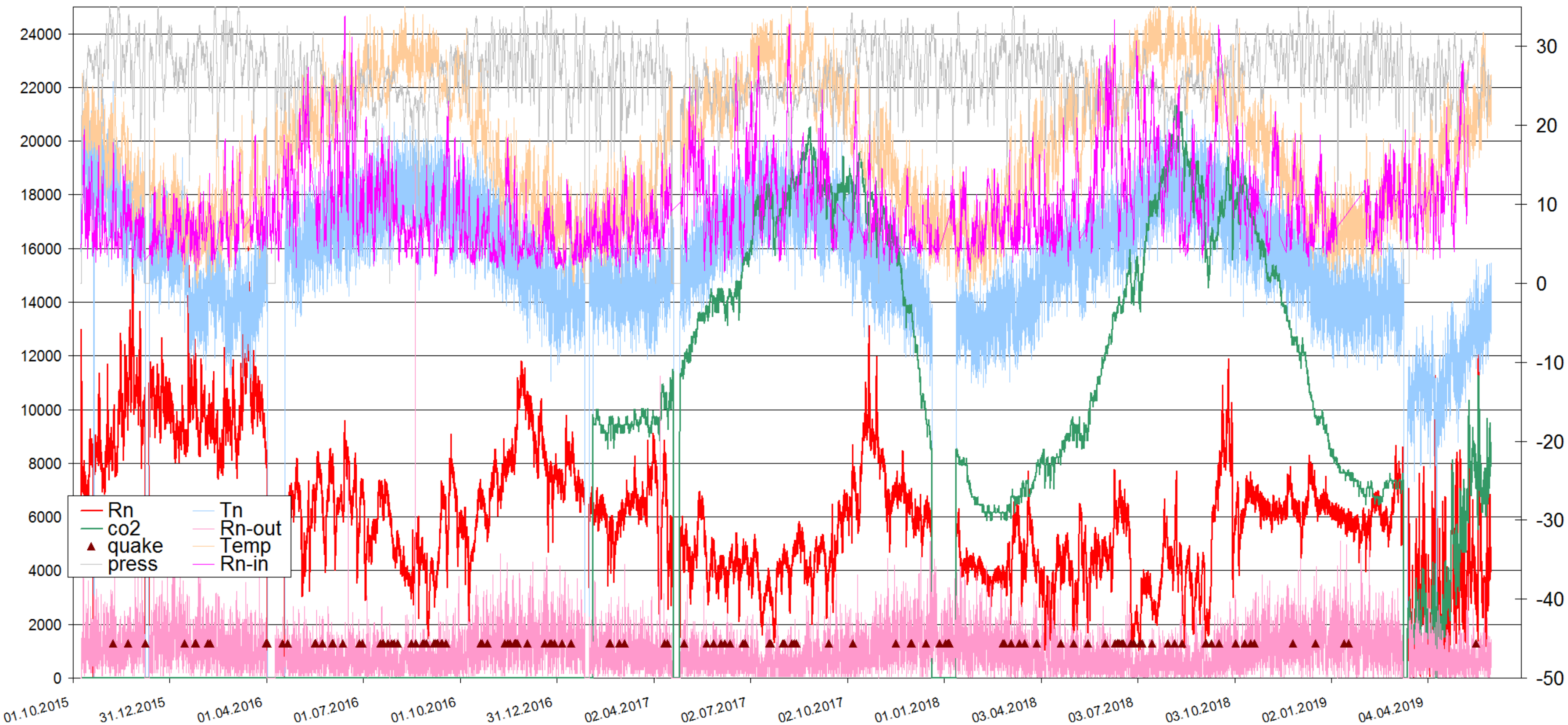
cross-correlation graph

Red: DR (unit: counts per 5s), blue: Rn concentration
DR measured wit a CzechRad monitor



Time series of outdoor Rn and NOx concentration at two stations a few km away (Berlin). The association is evident, although not all peaks coincide neatly. Similar graphs can be shown for PM10 and PM2.5. The association between Rn and O_3 is negative. **The association is of pure proxy type.**

4. Examples of Rn time series

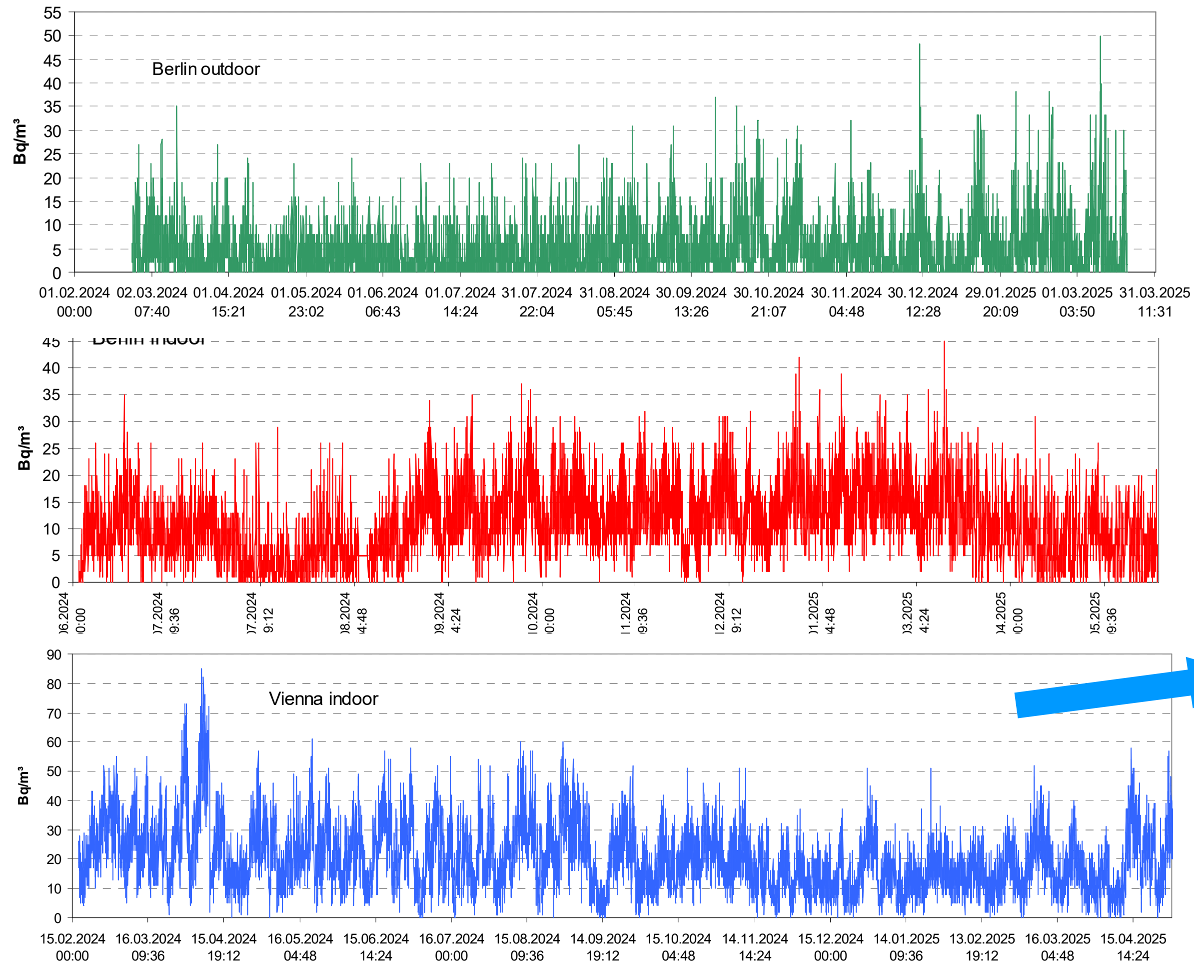


Rn and meteo time series, Chiba, Japan. Rescaled to fit into one graph. Left axis: Red: soil Rn concentration (Bq/m³); light blue: soil Tn concentration (Bq/m³) × 5; green: soil CO2 concentration (%) × 10,000; rose: outdoor Rn concentration (Bq/m³) × 300. Right axis: orange: temperature (°C); grey: barometric pressure (mbar), 20 + (press-1000)/2; pink: Indoor Rn concentration in a basement (Bq/m³) / 30; dark red triangles: earthquakes

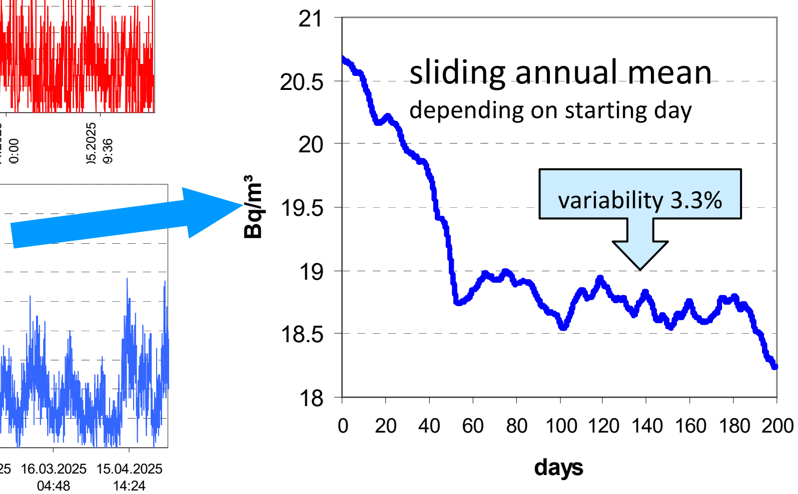
Measured with Alphaguards

		AM	SE	CV	min	max	n
Berlin outdoor	23.4.24-22.2.25 (1 y)	4.67	0.06	115%	0	48	8760
Berlin indoor	2.6.24-18.5.25	11.2	0.1	59%	0	45	8396
Vienna indoor	17.2.24-16.2.25 (1 y)	20.7	0.1	54%	0	85	8784

Bq/m³



- Very low concentrations
- Different patterns
- Weather episodes can be recognized



Series from last slide:

Mean concentrations are very low:
4.7 Bq/m³ Berlin outdoor
11.2 Bq/m³ Berlin indoor
20.7 Bq/m³ Vienna indoor
therefore of no radiological concern.

why?
- Low geogenic Rn potential: sand, alluvium;
- Second floor;
- Low Ra building materials

The variability is considerable: Remarkably high outdoor concentrations up to 50 Bq/m³ were observed.

The patterns of the series are different. While all show diurnal periodicity, which could be expected (not easily recognizable in the figure), their appearance is different. One probable reason is that the indoor series are subject to an influence of user behaviour, mainly opening windows, additionally to the meteorologically induced variability.

5) Radon as a tracer

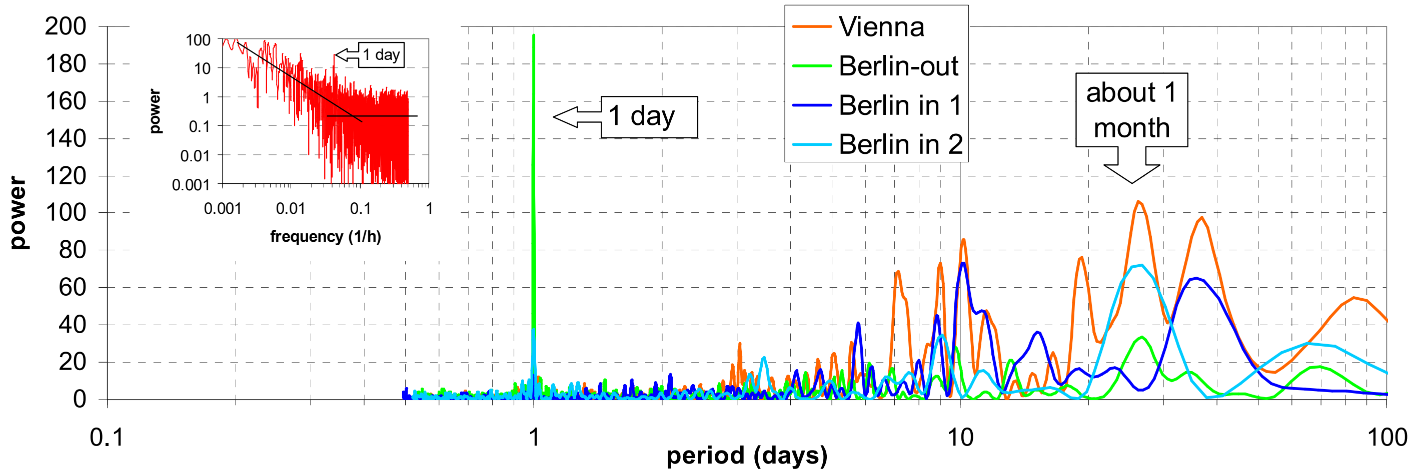
- Noble gas → no chemical interaction with ambient media
- Easy to measure
- Half life 3.8 d ≈ characteristic time of processes that determine ambient dynamic

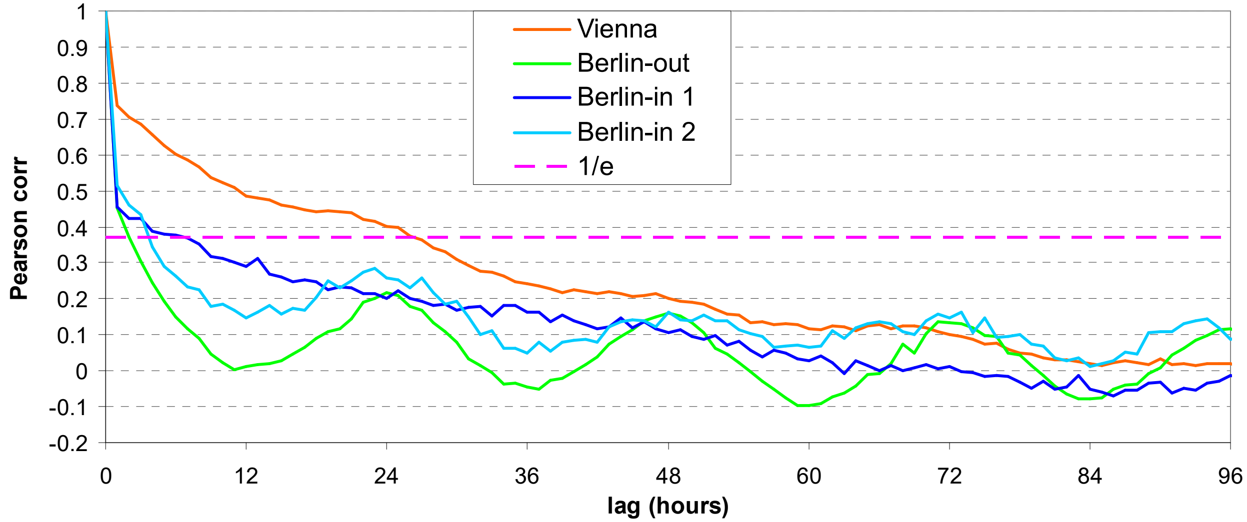
- Atmospheric transport: long-range, turbulence near ground, mixing conditions, proxy of aerosols and gases
- Hydrology: Groundwater tracking, karst studies
- NAPL monitoring in the ground: (non-aqueous phase liquids) – because of high solubility of Rn in these substances
- Tectonic studies: detection and characterisation of faults; Seismic prediction: so far not conclusive, but research is ongoing because of potential importance

6) Statistical analysis

- Time series Z(t); Components:
- Z_0 …. Offset
- m(t) …. long-term trend, for example linear
- $period_i$ (t) …. different periodic components:
  - diurnal, seasonal (yearly), tidal (lunar)
- aperiodic …. most complicated part! Reflects
  - weather episodes
  - seismic events
  - different temporal signature!
- Task: disentangling the components

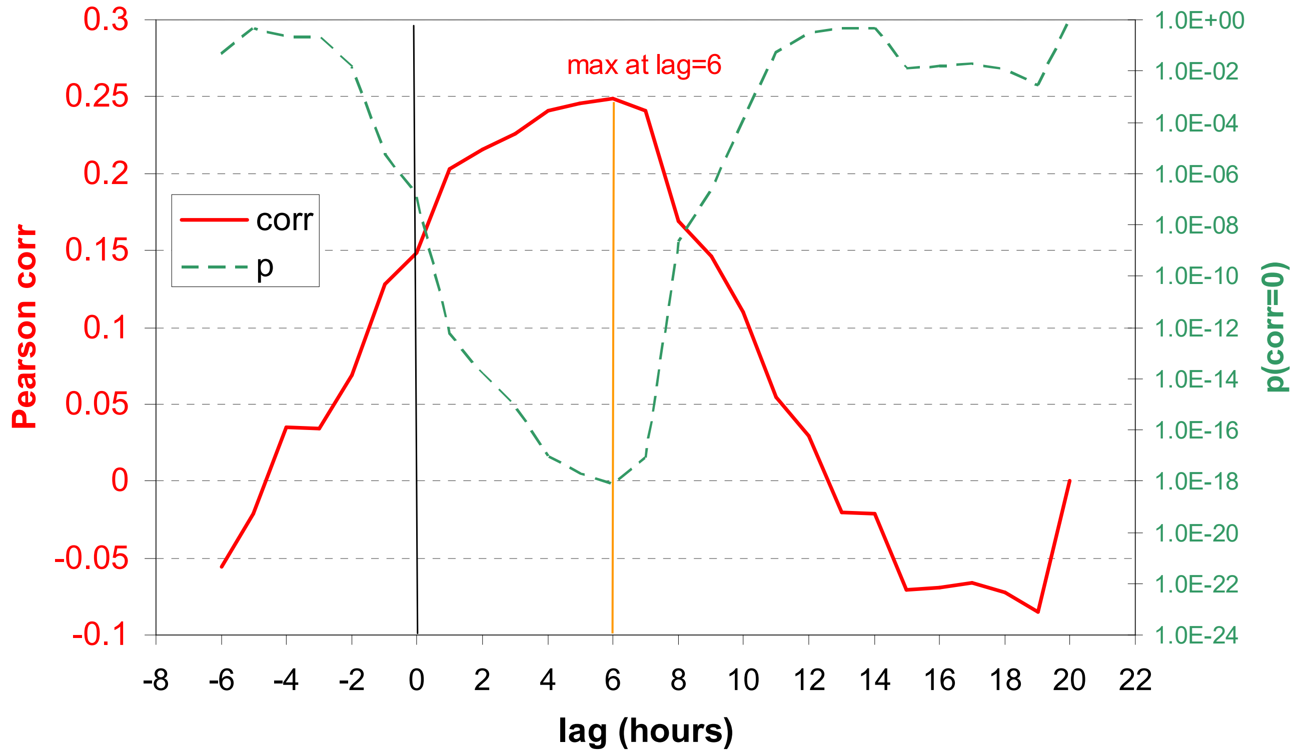
periodicity, autocorrelation





- **Fourier spectrum:** clearly 1 day period, perhaps ~10 days (typical duration of weather episodes?) and ~1 month (lunar tide??).
- **Autocorrelation:** correlation length = time until corr < 1/e: Berlin outdoor: 2 h, Berlin indoor 4 – 6 hours, Vienna indoor: 26 hours

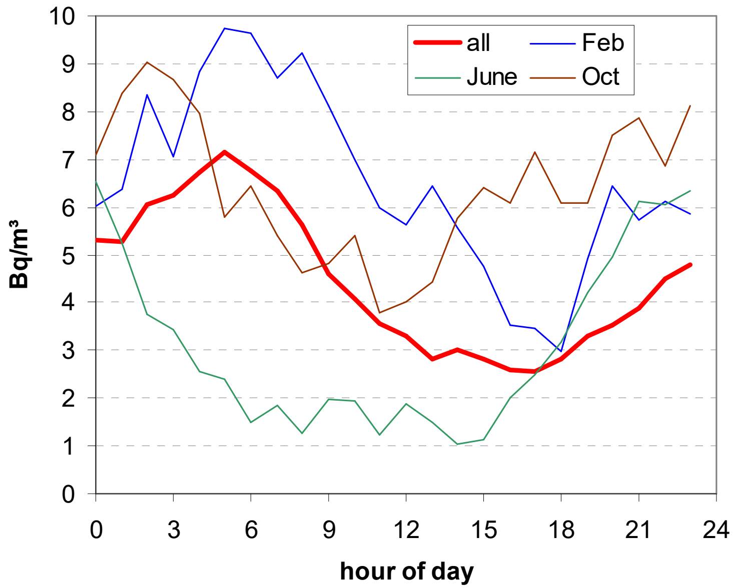
cross-correlation

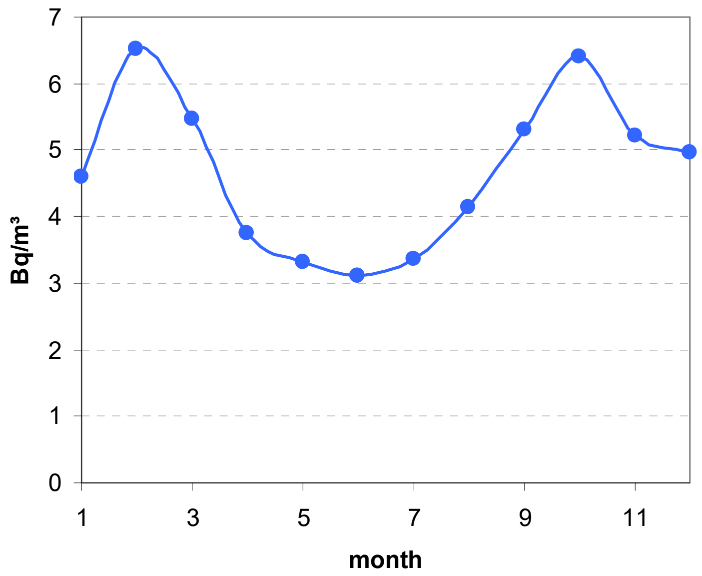


Cross-correlation indoor / outdoor Rn, Berlin:

1) they are correlated
2) outdoor Rn is 6 hours ahead indoor
3) Indoor Rn strongly controlled by outdoor Rn

diurnal and seasonal pattern



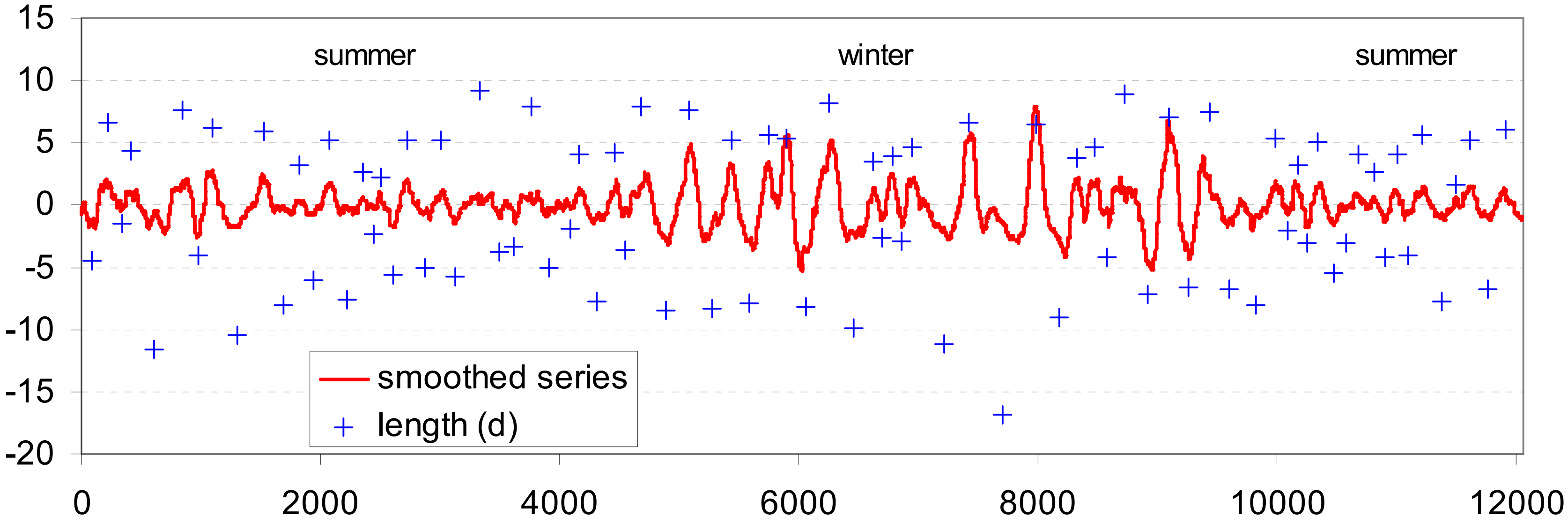


Outdoor Rn, Berlin

- Rn concentration increases during night, maximum usually in the morning, minimum: mid-afternoon.
- Reason: atmosphere more stable (less turbulent) at night. After sunrise, turbulence increases → dilution.
- Time delay due to physical inertia of the atmosphere as physical system.
- Well-known effect!

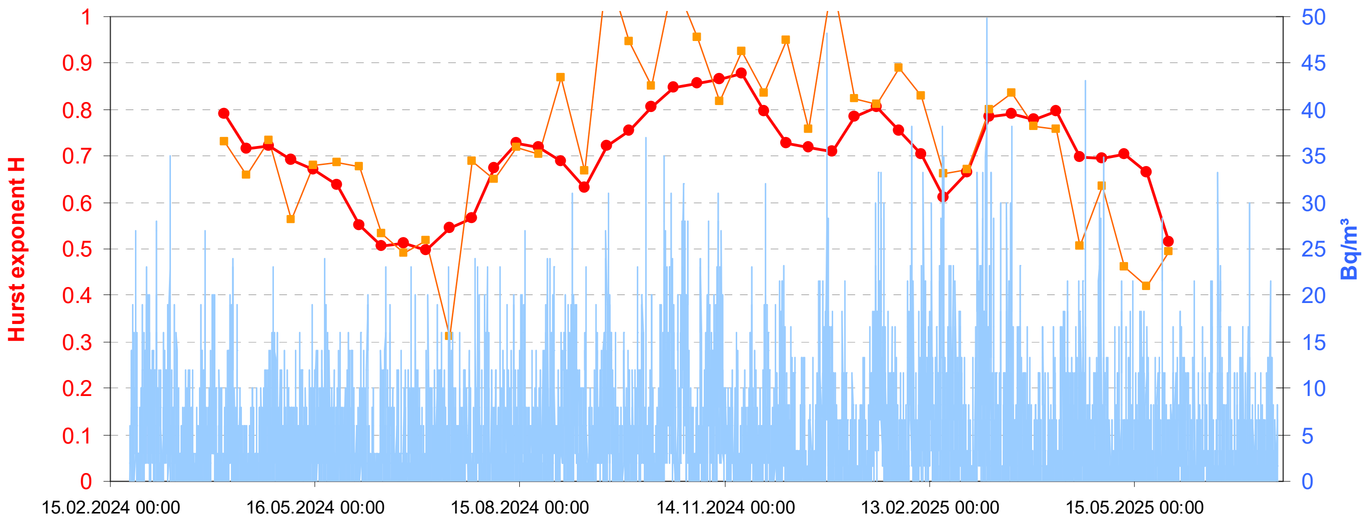
aperiodic "synoptic" variability

- Aperiodic variability of outdoor Rn mainly reflects meteorological episodes of sunny or rainy weather or passing low or high pressure systems.
- Assessed by applying band-pass filters which remove short- and long-term variability: here band = (4 d, 20 d), simple AM filters.
- Lengths or durations of high- and low-Rn episodes: 5.2±1.9 and 6.2±3.2 days



Hurst analysis

- Originally invented for hydrological dam planning around 1950 (Assuan dam, Hurst)
- The **Hurst exponent H** measures "persistence" of a phenomenon: Persistence (H>0.5): tendency that high (low) values are followed by high (low) values; Antipersistence (H<0.5): tendency that a high value is followed by a low value. H=0.5: White noise.
- Radon series: H≈0.6 – 0.7 (outdoor) and 0.7 – 0.85 (indoor), consistently by several authors.
- New finding: H seems itself to be fluctuating … for whatever reason. Perhaps linked to climatic stability.



Red and orange: Hurst exponent calculated in two methods for 2000 h long sub-series centred on the dots. Blue: The original outdoor Rn series.

Is Radon a stationary process?

- Stochastic process Z … defined on a space-time interval U, autocorrelative structure
- Strictly stationary: $F_x(Z) = F_{x+\xi}(Z)\ \ \forall x+\xi \in U$ F distribution over (hypothetical) realizations of Z
- Weakly first order: $E(Z(x))=E(Z(x+\xi)) \leftrightarrow E(Z(x))=E(Z(x'))\ \forall x+\xi \in U$ or $x, x' \in U$
- Second order: $E(Z(x)\ Z(x'))=E(Z(x+\xi)\ Z(x'+\xi'))$; in particular, importantly: autocorrelation depends only on the lag x-x' but not on x.
- Related to ergodicity: in the form of Birkhoff theorem, much simplified: spatial mean of an ensemble at each time = long-term temporal mean of each realization (particle).

Why is this relevant in radon science?

- Usually one assumes that a Rn process is stationary; i.e., it has a constant long-term (>> time scale of fluctuations) temporal mean. This is the condition for feasibility of regulation, because a reference value is conceived independent on the time of verification.
- But what if for some reason Rn concentration has a trend, i.e. changes apart from recurring fluctuations (which do not contradict stationarity)? In this case, the quantity "long-term mean Rn concentration in a building" does not exist $\Rightarrow$ cannot be compared with a reference value.
- Possible reasons: Climatic change, which generates a trend in Rn exhalation due to changing soil properties.

Second order stationarity

- A key concept in spatial modelling, essential for kriging.
- Anomaly can be conceptualized as spatial "pocket" in which the autocorrelation structure is different from the one of the "background" $\rightarrow$ interpolation fails, can create artefacts and spurious phenomena.
- Not quite well known how machine learning algorithms are affected.

Stationarity looks innocent but is in fact a tricky concept. Terminology is not consistent!

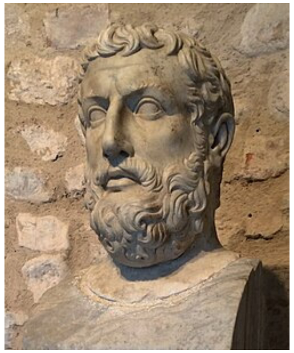
Frequentist vs. Bayesian

- In "ordinary" (frequentist or Laplacian) statistics, one assumes a "true" quantity Z, and given uncertainty and variability (assumed known), one derives the distribution of the measured quantity F_Y, Y=f(Z), f=measurement or observation process.
- From F_Y, derive E(Y), Var(Y), confidence intervals,…

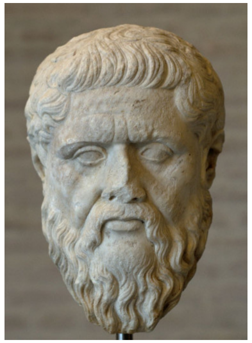
BUT:

- We do not know Z; in fact we are interested in Z, but know only one or several observations Y, e.g. the readings of a measurement instrument.
- We want to know E(Z) conditional to observed Y (more general F_Z, most probable Z, "credibility intervals" of E(Z)…)
- →Bayes statistics
- Example: a Rn monitor gives the result Y=0 Bq/m^3 because in the measurement interval (e.g. 10 minutes) no counts were registered. But this can happen for a stochastic (here: Poisson) process whose true value E(Z)>0. (Physically, truly 0 does not exist.)
  So, how to find an estimate of E(Z)|Y=0 ?
  → Bayesian inversion… not entirely trivial!

Interestingly, this has a long history:



Parmenides, late 6th – mid 5th cent. BC

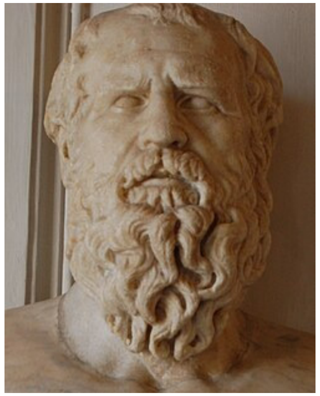


Plato, ca. 428-348 BC

Pierre Simon Laplace, 1749-1827

frequentist approach: also Gauss and others

"truth" = αληθεια vs.
"opinion" or observation = δοξα, understood derogatory



Heraclitus,
ca. 520- ca. 460 BC

Reversing the roles of aletheia and doxa Aristoteles inverted Platon and stood him from the head on his feet (like Marx with Hegel)
Plato: ουσια, ousia (essentia) = ideas
Aristoteles: essence of singular things

Aristoteles, 384-322 BC

Thomas Bayes, ca. 1701-1761

Chaoticity

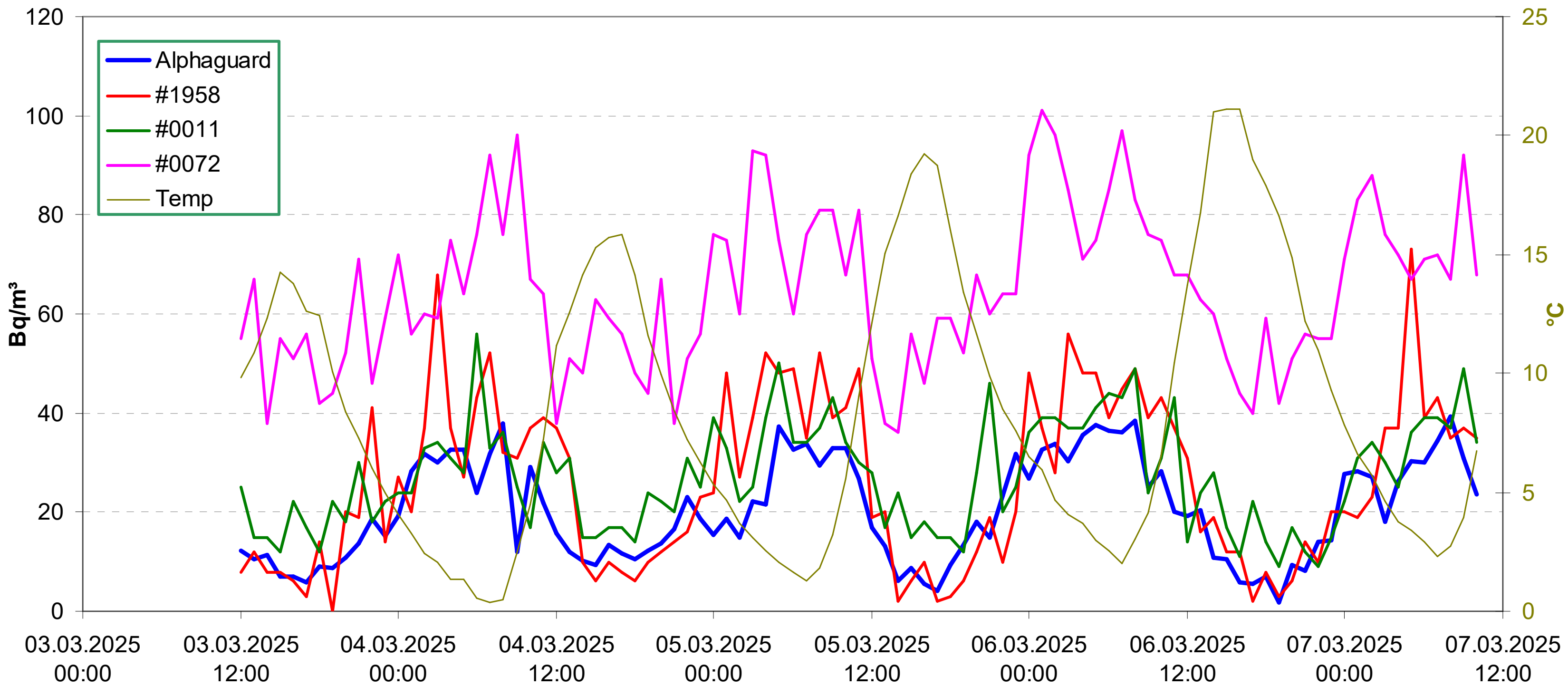
Chaotic:

- Construct the phase space of a system which is represented by the time series. For Rn series a few authors found ca. 5-dim. phase spaces.
- Follow neighbouring trajectories in the phase space and measure how they separate with time. If the separation $d \sim \exp(\lambda\, t)$, the system is called chaotic, with Lyapunov exponent λ. (Strongly simplified!!)
- A chaotic system cannot be predicted for longer time, because of the divergence of trajectories which are initially very close.
- For Rn series: investigated by different authors, but no consistent results. a) Rn is not chaotic; b) λ too small to be detectable.
- $\rightarrow$ further research…

Annex: Secondary calibration of consumer-grade Rn monitors

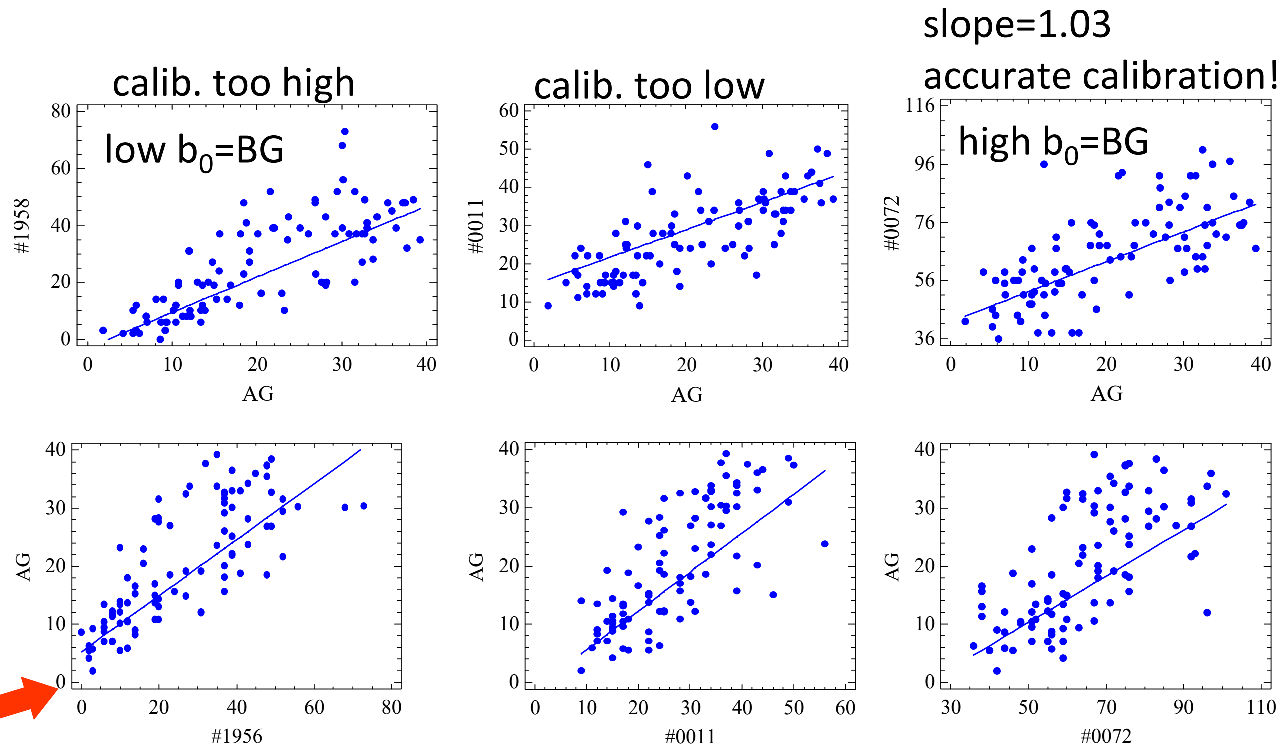
Experiment performed together with Jana Vaupotič, Josef Stefan Inst., at the meteorological station, Ljubljana

- Low-cost monitors are practical as the enable diverse uses
- But the lo cost entails compromises in QA, in particular individual calibration...
- ... default calibration of the RadonEye as delivered from the factory is not very reliable. Biases up to 20% must be expected.
- Easiest and most economic way: through comparison with a calibrated monitor



Parallel exposure of 3 RadonEyes and an Alphaguard (together with local temp.)

- Assume that the readings of the Alphaguard (AG) represent the true Rn concentration.
- To **characterize** an instrument (Instr), estimate **E(instr|AG)**
  - Done by weighted OLS regression, since a linear relationship can be reasonably assumed.
  - Instr=b_0 + b_1 AG + ε.
- Reversely: **Interpreting** a reading of Instr, i.e., estimating the true Rn concentration:
  - True = AG = **E(AG|Instr)**
  - AG = a_0 + a_1 Instr + δ.
- weights $1/\sigma_i^2$



	b_0	b_1	r^2(adj)
#1958	-3.0 ± 1.3	1.25 ± 0.08	0.71
#0011	14.4 ± 2.0	0.72 ± 0.08	0.46
#0072	41.8 ± 2.4	1.03 ± 0.11	0.56

Conclusions

- ***Radiation protection:*** Primary and most frequent use of measuring Rn with active devices is radiation protection, in particular if time discriminating results are needed in workplace characterization.
- ***Tracer studies:*** Application of Rn as tracer is well established. Many of the methods rely on time series. Study on association between Rn concentration and its controls and proxies will be continued.
  Seismic prediction: discussed controversially. Apart from its potential benefit it contributes to progress in analytic – experimental and statistical – methodology.
- ***Quality assurance:*** We call on professional metrological institutes to enable cheap secondary calibration for users of consumer-grade instruments. The cost is minimal: a well primary-calibrated and QAed high-end instrument such as Alphaguard or RAD-7/8 must be operated simultaneously with the instrument to be secondary-calibrated in a place where a high Rn dynamic can be expected for a few days. This costs next to nothing. The statistical procedure which is easy can be left to the individual users.
- ***Rn time series statistics:*** The analyses lead to insights into the physical nature of Rn dynamics and the ambient dynamic which dives it.
  As next step, we plan to connect the results to analogous ones of the predictors of outdoor Rn, which are mainly meteorological variables, and of proxies such as atmospheric pollution data, for example PM2.5 and NOx. Important: Quantification of mixing layer height as predictor.
  Some problems, notably the question of the chaotic nature of Rn concentration, are unresolved.
- ***Citizen Science:*** We think that low-cost active Rn monitors have a considerable potential in Citizen Science. The possibility to observe Rn dynamic in almost real time may not only stimulate scientific curiosity, but can decentralize data acquisition and altogether democratize science. Information on time-discriminating Rn concentration reflecting living habits and working patterns is important for Rn policy.

Thank you!