Università degli Studi di Ferrara

GAMMA RAY SPECTROSCOPY FOR EVALUATING SOIL WATER CONTENT IN CULTIVATED FIELDS

Supervisor:

Prof. Fabio Mantovani

Candidate:

Michele Franceschi

Co-supervisor:

Dr.ssa Virginia Strati

A.A. 2022 - 2023

SUMMARY

- Proximal gamma ray spectroscopy (PGRS) for evaluating soil moisture
- Soil Water Content (SWC) evaluation
- Experimental sites and instrumentation
- Analysis method of a gamma ray spectrum
- Validation of the results
- Conclusions and future perspectives

Monitoring the water content through Proximal Gamma Ray Spectroscopy (PGRS)

- Monitoring **Soil Water Content (SWC)** in cultivated fields assumes particular relevance since water consumption in agriculture accounts for approximately 70% of global freshwater consumption.

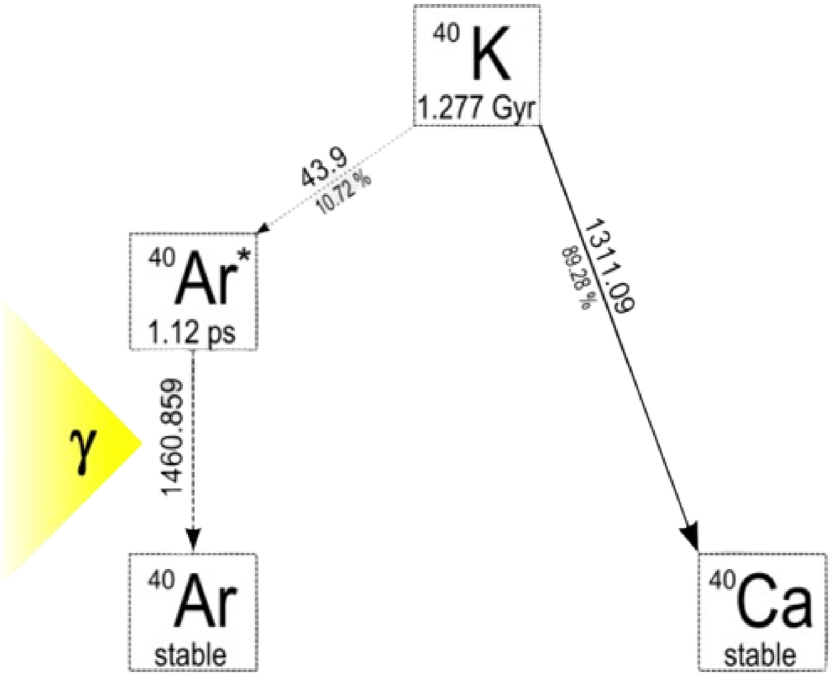
- Among the possible methods that can be used for determining SWC, PGRS technique allows to obtain **real time measurements** leaving the soil undisturbed.

- The main concept at the basis of this technique is that the **photons** produced in the ground by the decays of radioelements are **attenuated proportionally** to the amount of **water stored in the soil**.

Radioactive decay of the elements in the soil

- Radioactivity is a **natural phenomenon** that occurs when an unstable nuclide spontaneously reaches a condition of greater balance, emitting radiation in the form of photons and/or other particles.

- Earth's natural radiation comes from the radioactive substances synthesized during the formation of solar system that possess **half-lives long enough** to justify their current existence and constant abundance in time.

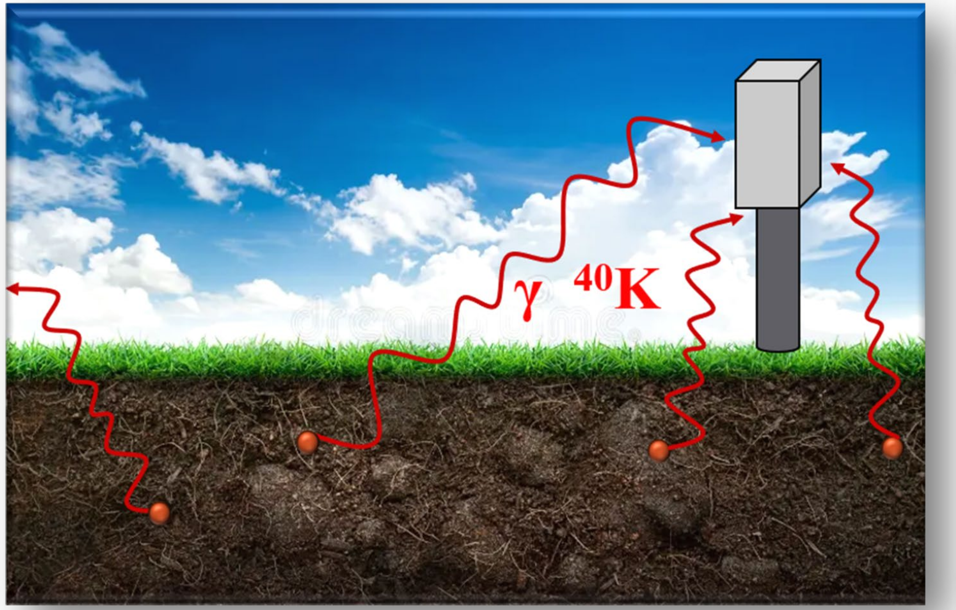


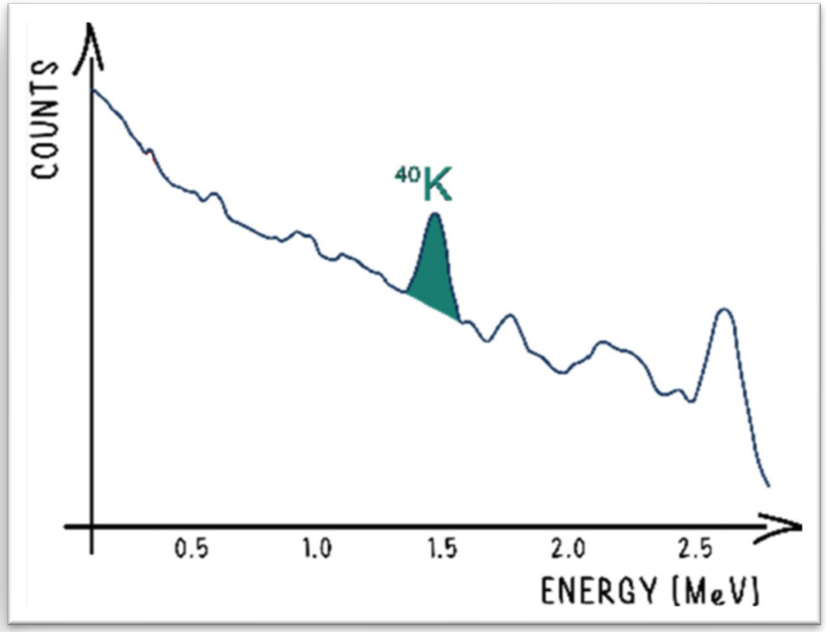
Radioelement	Isotopic abundance (%)	$T_{1/2}$ (yrs.)	Average soil abundance
K	$^{40}K = 0.01$	$1.3 \cdot 10^{9}$	2 %
U	$^{238}U = 99.3$ $^{235}U = 0.7$	$4.47 \cdot 10^{9}$	2.5 ppm
Th	$^{232}Th = 100$	$1.39 \cdot 10^{10}$	12 ppm

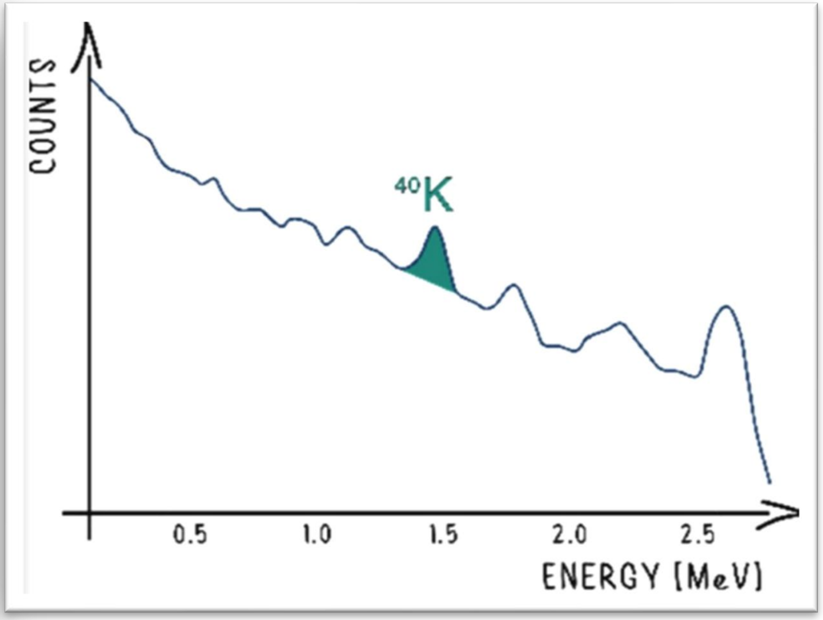
K, U, Th

γ spectroscopy

Attenuation of the potassium gamma signal







- K concentration in agricultural soil can be considered homogeneous in space and constant over time.

- The presence of **water**, due to its **higher attenuation coefficient**, reduces the number of photons associated to ^{40}K decay (1.46 MeV) impinging the detector, resulting in a **lower populated peak** in the relative gamma ray spectrum.

Experimental sites

- Firenze, Italy, greenhouse (GH), farm, horticultural cultivations, dimensions: (11 x 89) m.

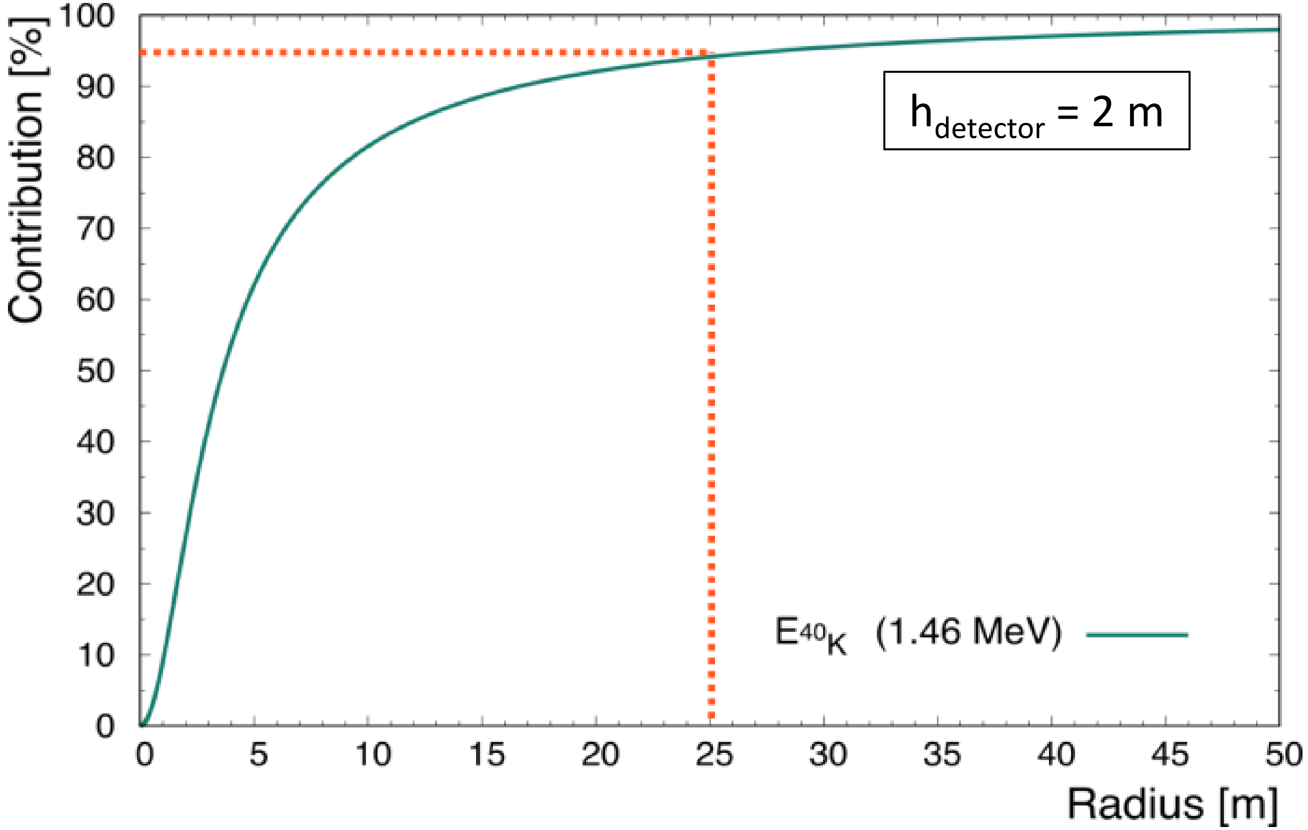
- Zaragoza, Spain, wheat field (WF), “Estación Experimental de Aula Dei” research center, cereal cultivations, dimensions: (85 x 45) m.

Experimental setup

h = 2.4 m

h = 2 m

Component	GH site	WF site
Scintillation crystal NaI(Tl)	V = 0.1 L	V = 0.4 L
Photomultiplier tube (PMT)	Hamamatsu R6231 (10 stage)	
Multi Channel Analyzer (MCA)	2048 channels, remote controlled acquisition	



- For a detector placed at height of 2 m nearly 95% of ground radioactivity comes from a ~ **25 m radius** area.
- Concerning the depth profile, nearly 95% of ground radioactivity comes from a ~ **25 cm soil layer**.

From ^{40}K counts to Soil Water Content (SWC)

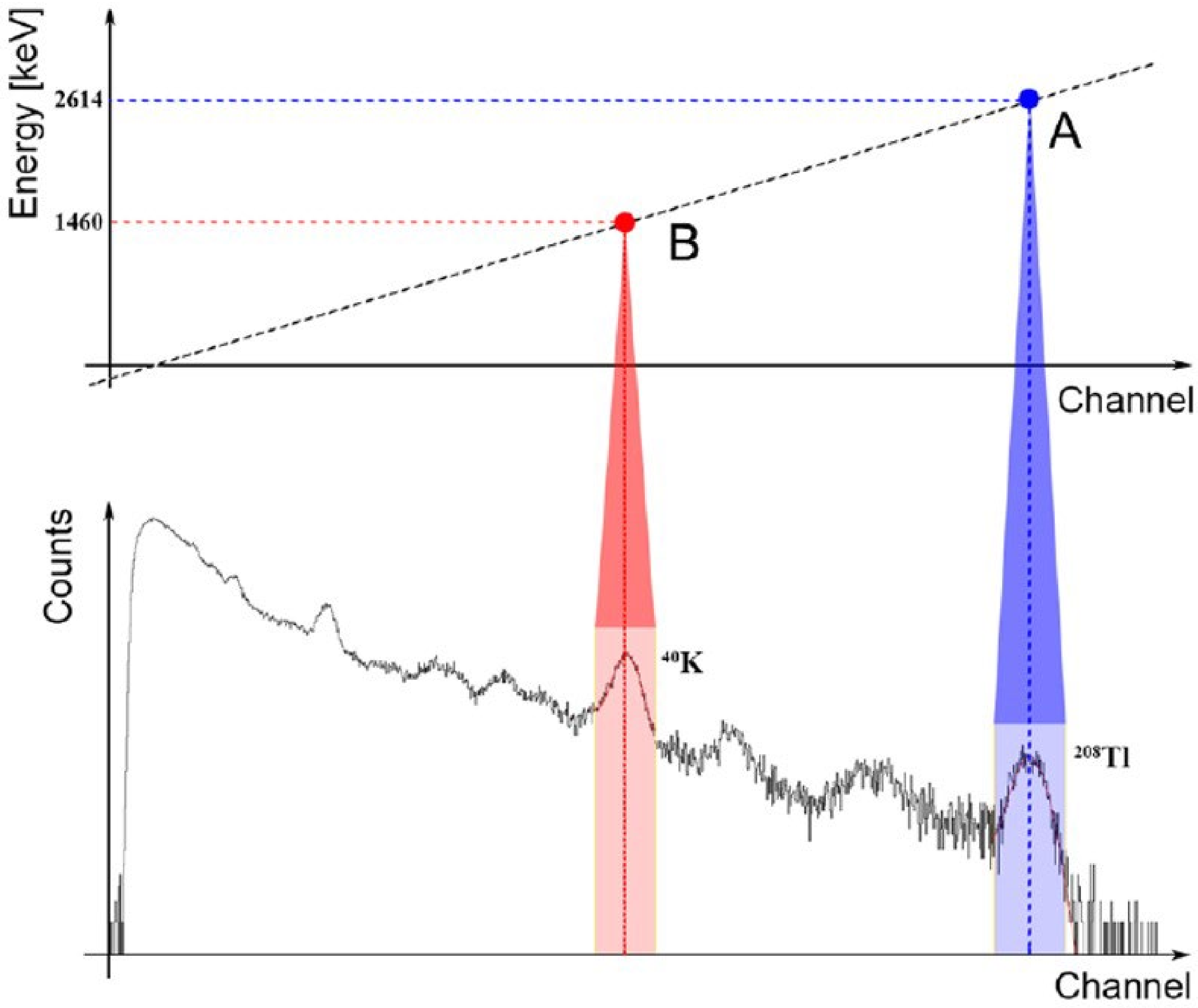
The knowledge of the current value of SWC of the investigated field requires some **input information** given by:

$$SWC\ (t) = \frac{S_K^{Cal} \cdot \Lambda_K(t)}{S_K(t)} \cdot \left[\Omega + w_G^{Cal}\right] - \Omega$$

- $S_K(t)$ (cps) are the **net counts** in the ^{40}K photopeak, at **time *t***;
- S_K^{Cal} (cps) are the **net counts** in the ^{40}K photopeak, at the **time of calibration** under bare soil conditions;
- w_G^{Cal} (kg/kg) is the **soil water content** determined from **independent measurements** at the time of calibration;
- Ω is a constant calculated on the basis of the chemical composition of the investigated soil;
- $\Lambda_K(t)$ expresses the **time dependent correction** that accounts for the water contained in the **biomass**.

Energetic calibration of a gamma ray spectrum

In the output file of the MCA the photon detected are organized in **2048 channels**, but no information concerning their energies is provided.

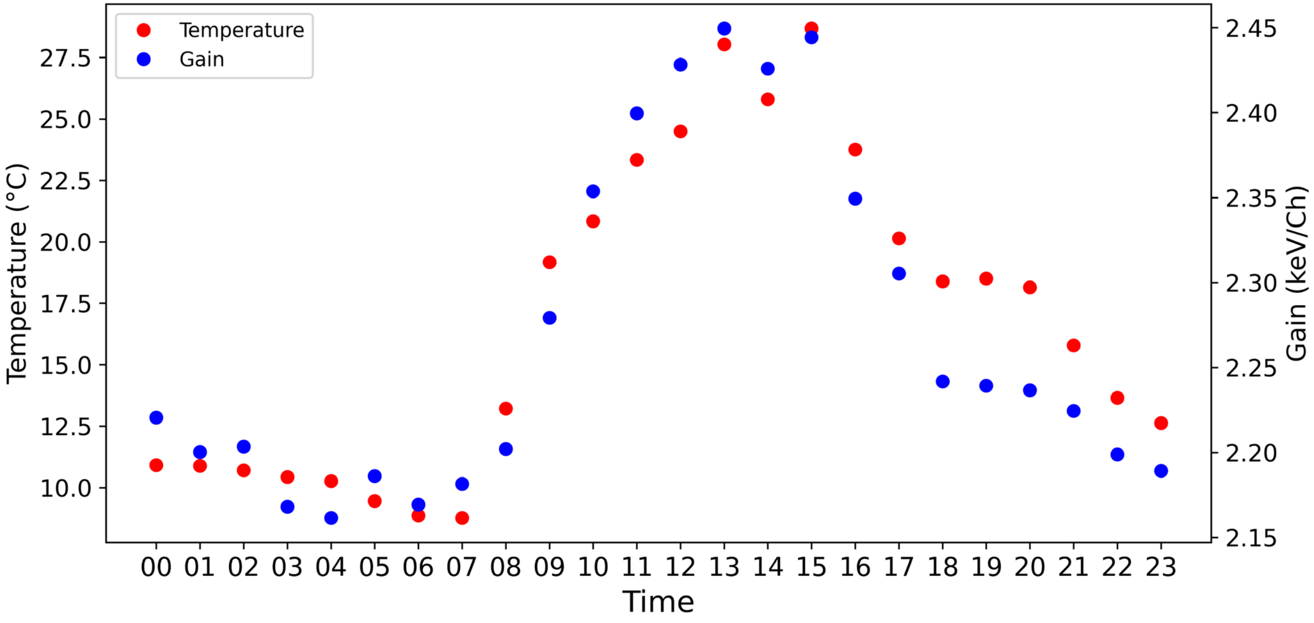


The **energetic calibration** procedure allows to determine the **linear relation** existing between **channel and energy** on the basis of well-known spectral structures:

$$E(keV) = G\left(\frac{keV}{Ch}\right) \cdot C(Ch) + I(keV)$$

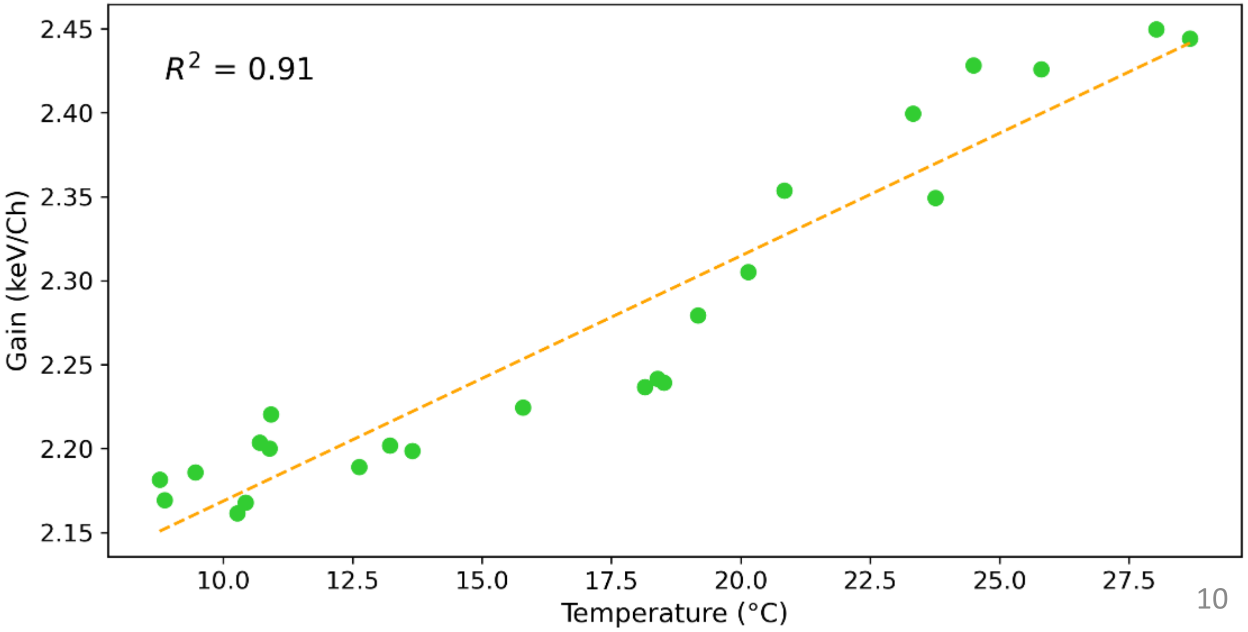
- $G\left(\frac{keV}{Ch}\right)$: slope of the calibration line, also referred to as "gain".
- $I(keV)$: intercept of the calibration line.

Gain – Temperature dependence



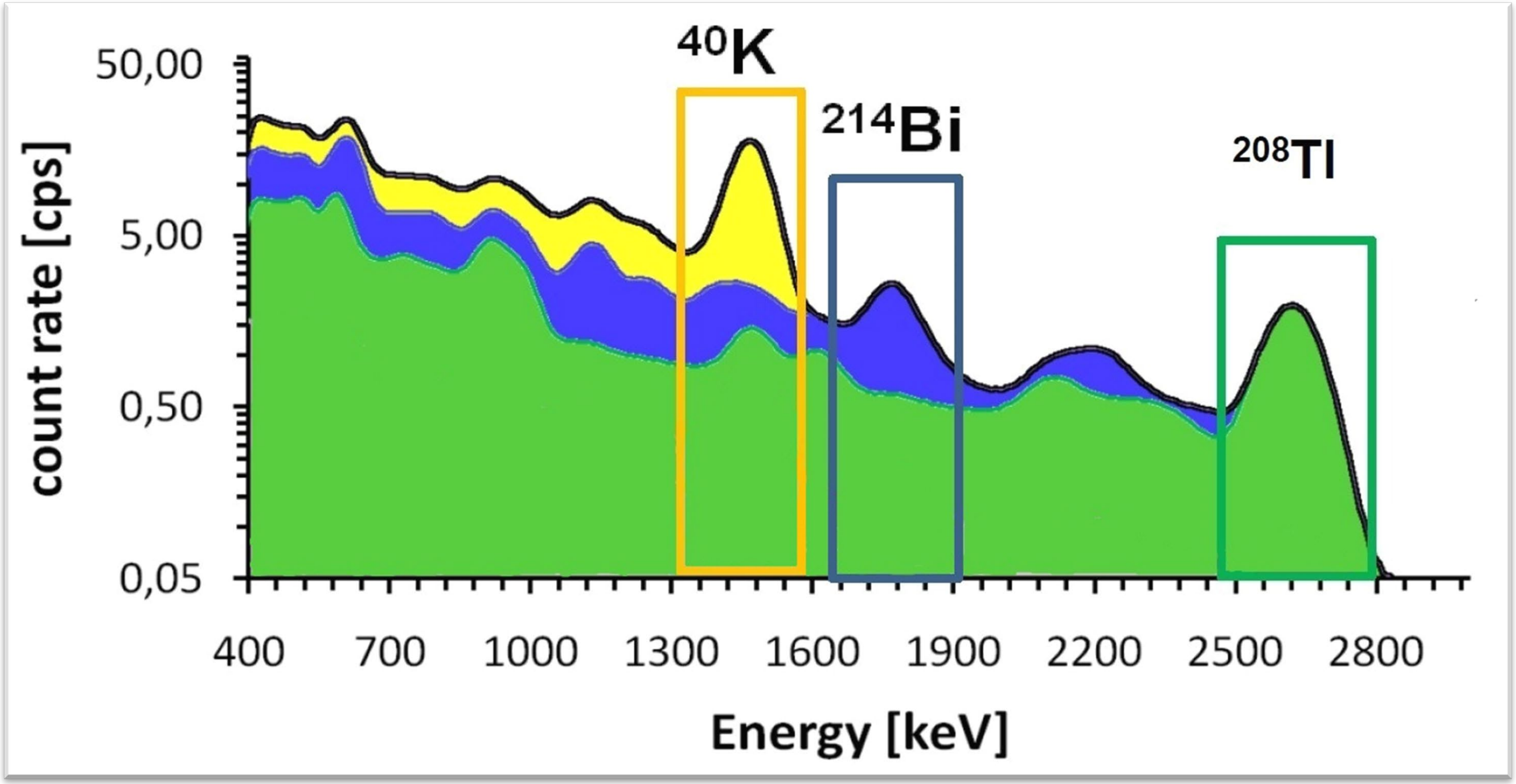
- Spectra from hourly acquisitions of **19/04/2023** in the **GH** site.
- Gain (G) is obtained through the calibration procedure of each spectrum while air temperature data were recorded by the meteorological station installed in the site.

- Maximal change in gain recorded: ~ 0.3 keV/Ch (08:00 – 13:00).
- If the acquisition time is limited to 1h the maximal change in gain registered is ~ 0.08 keV/Ch.
- This is the reason **won't be calibrated** spectra **longer than 1 h**.



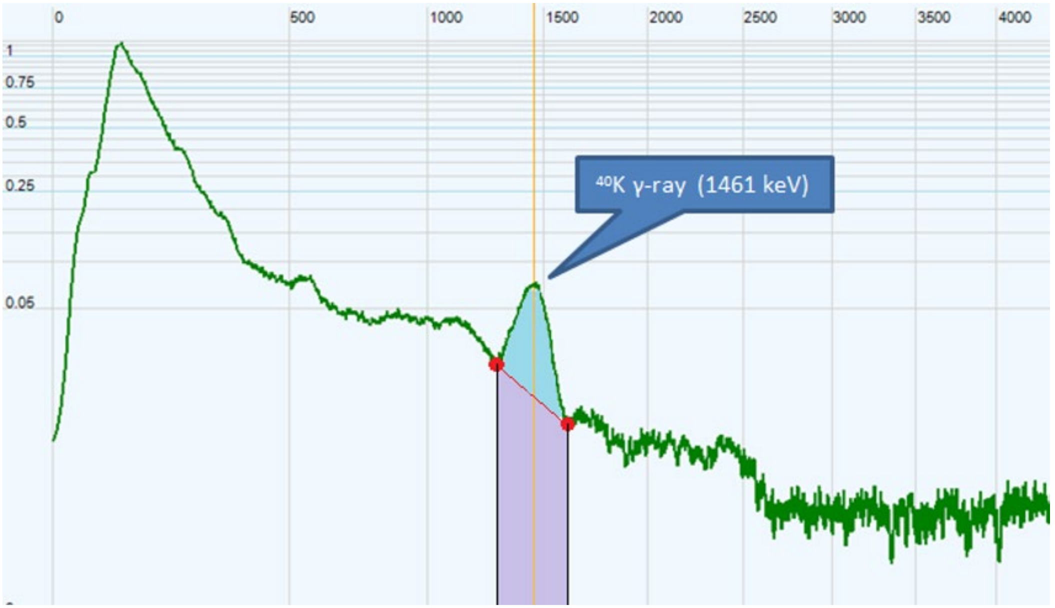
Evaluation of the net counts in the ^{40}K spectral region

- The **counts** registered in the ^{40}K region are **not solely referred to potassium** but also to other radioelements counts, therefore it's necessary to perform a **removal of the background** obtaining the "**net counts**" associated to ^{40}K decay.



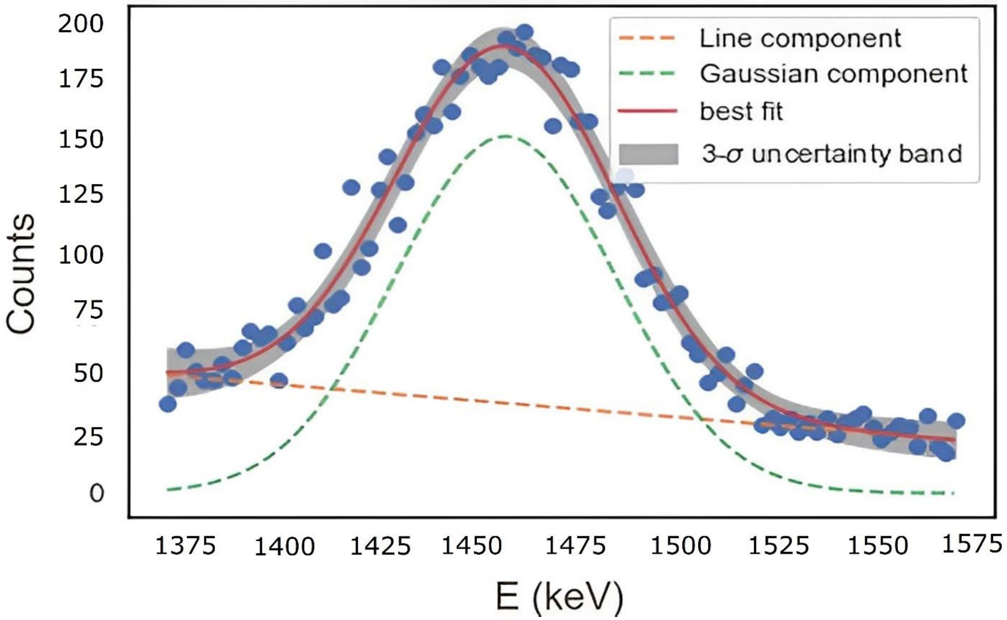
Implemented methods for inferring net counts

1. Trapezium method



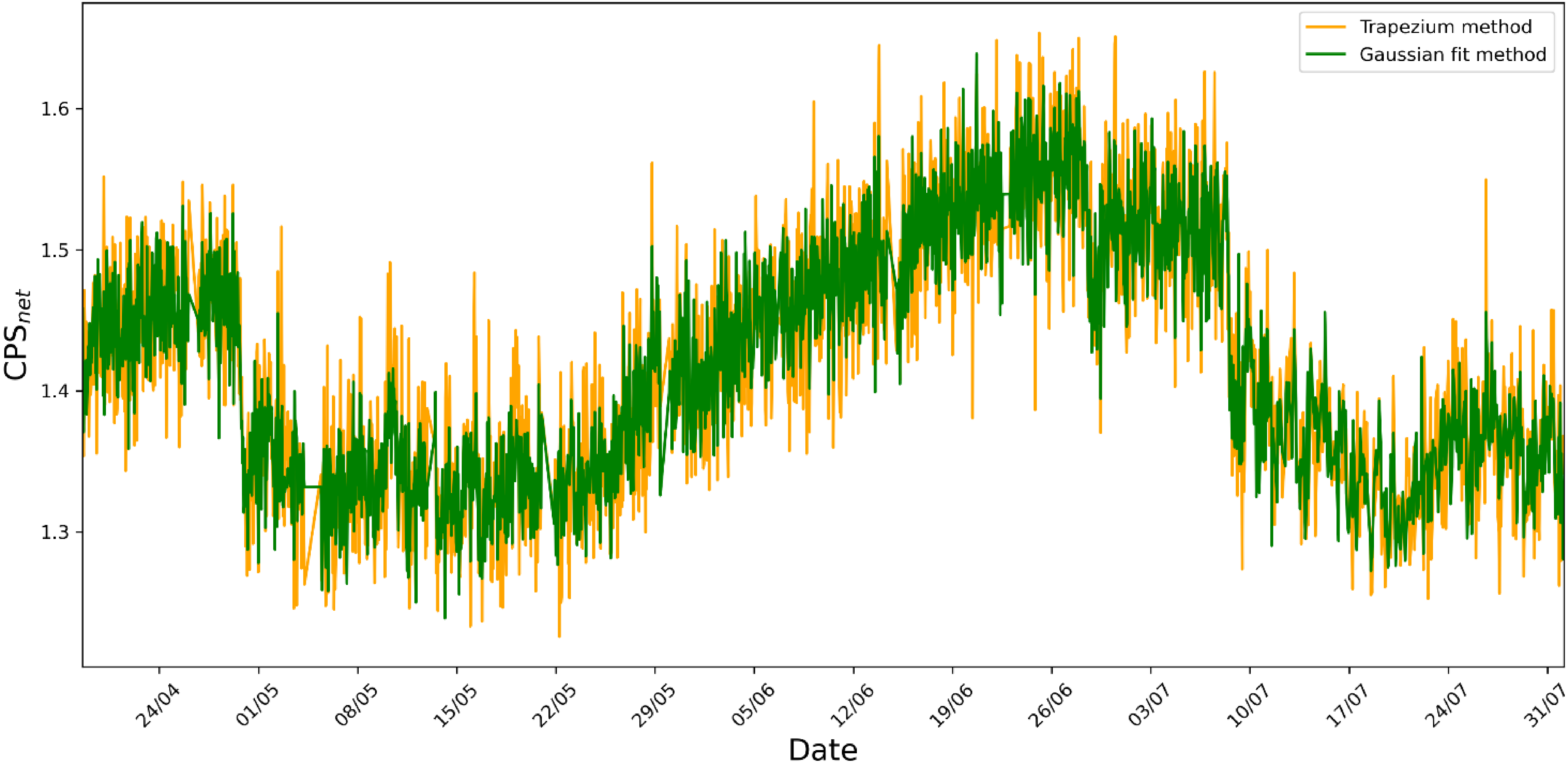
- Easier to implement
- Faster run time
- Less reliable

2. Gaussian fit method



- Harder to implement
- Higher run time
- More reliable

Comparison of the two methods

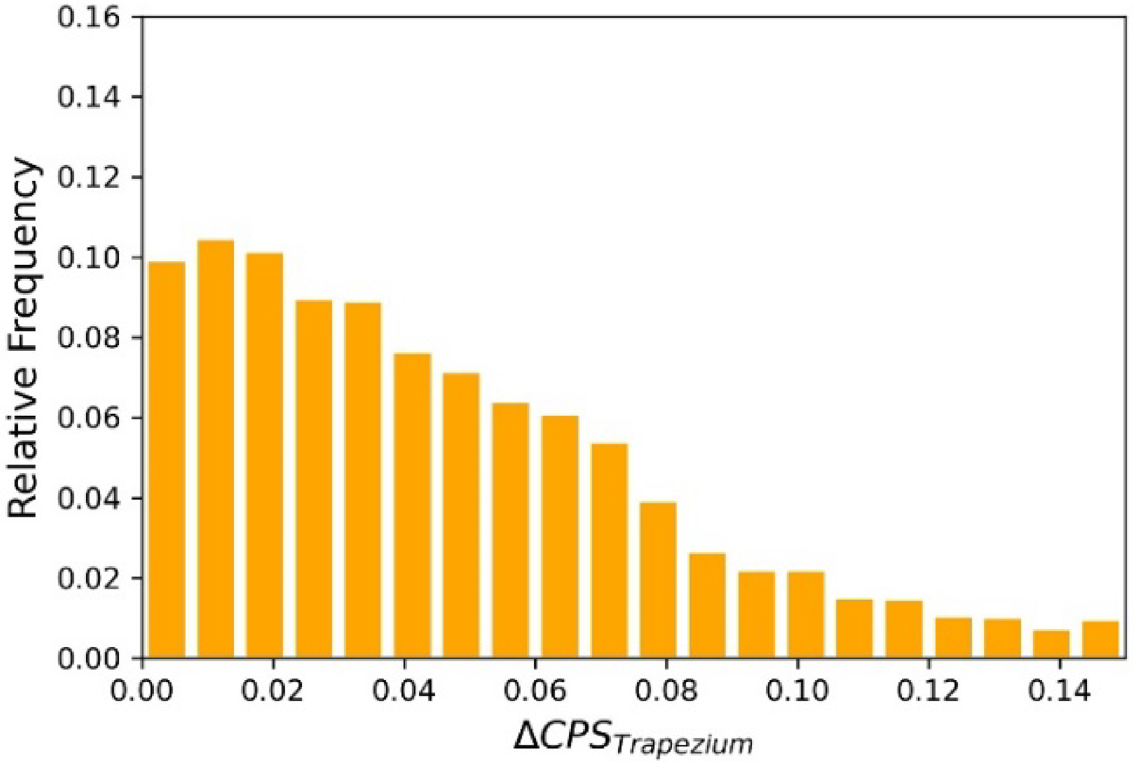


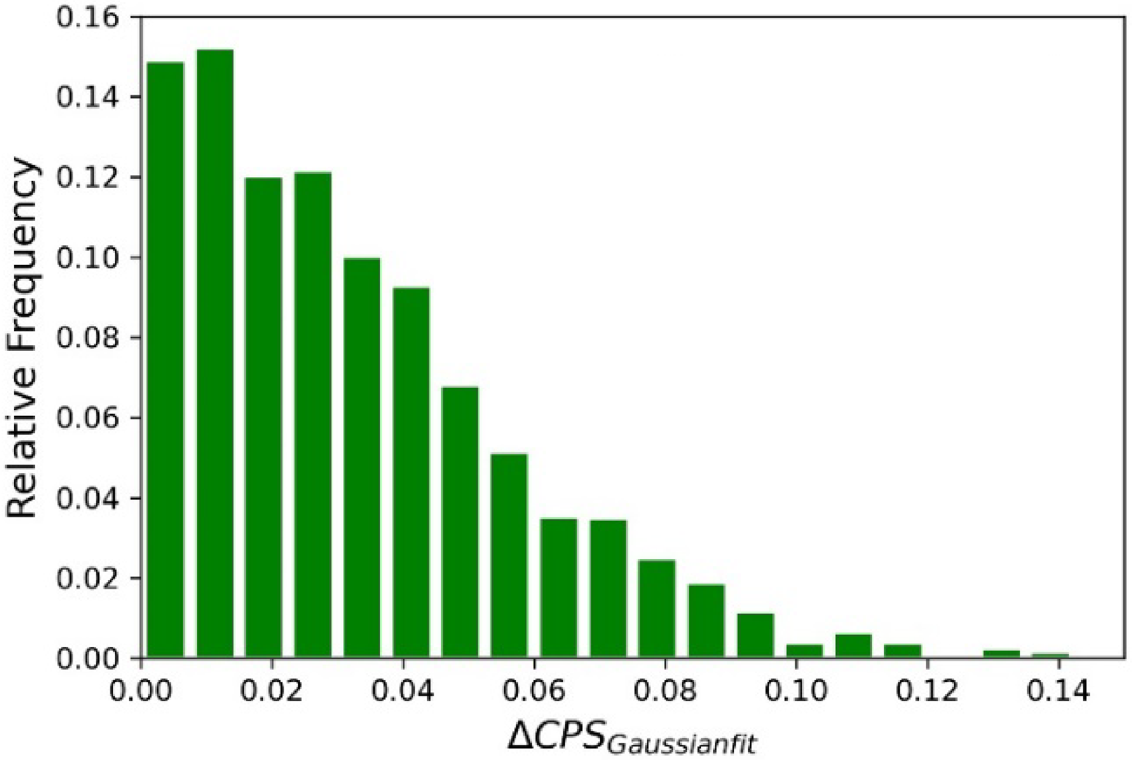
Comparison of the two methods

The goal is to reduce the median value of the distribution of the fluctuations between two consecutive measurements of CPS (ΔCPS) below the statistical error, i.e. 2%.

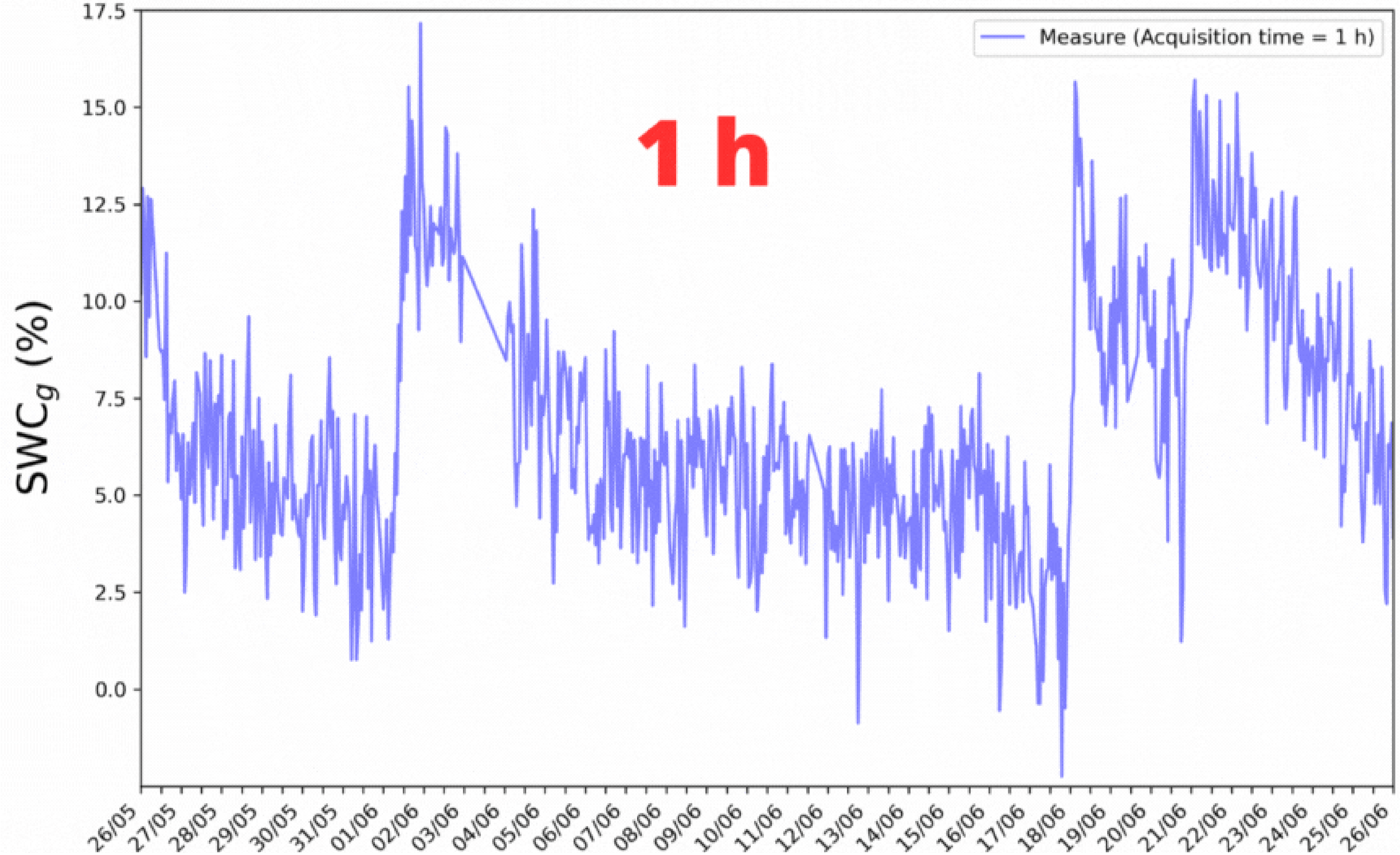
$$\Delta CPS = |CPS_{net}(t = i) - CPS_{net}(t = i + 1\,h)|$$

Method	Median $\boldsymbol{\Delta CPS}$	Mean CPS	$\epsilon = {\boldsymbol{Median \Delta CPS}}/{\boldsymbol{Mean\ CPS}}$
Trapezium	0.0389	1.4236	2.73%
Gaussian fit	0.0273	1.4232	1.92%



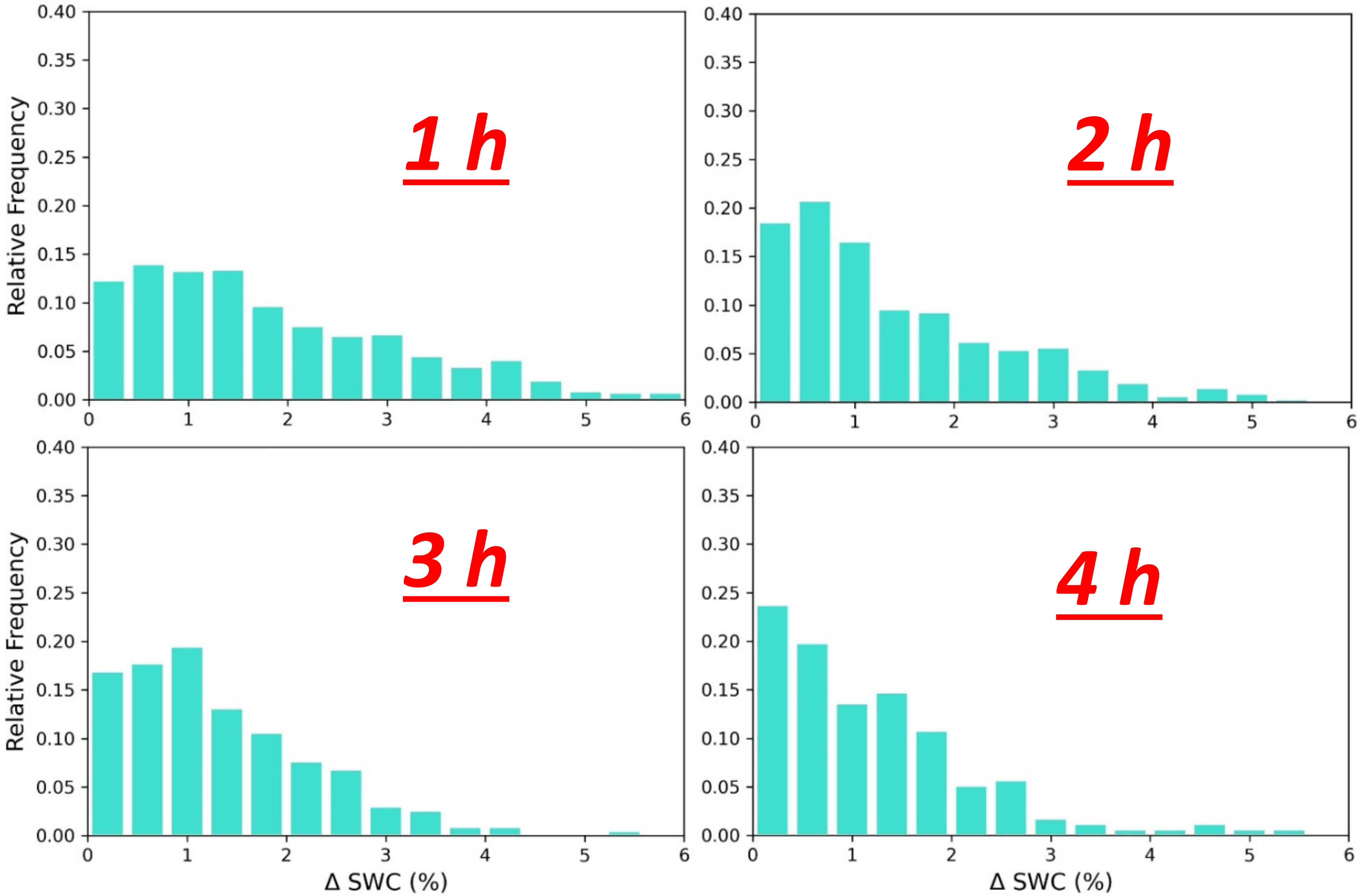


SWC temporal profile in WF site



Results of the different acquisition times

For the choice of the **most suitable acquisition time** of a single spectrum the histogram of the quantity $\Delta \boldsymbol{SWC}$ was realized for 4 different acquisition times in order to infer the corresponding median value of the distribution.



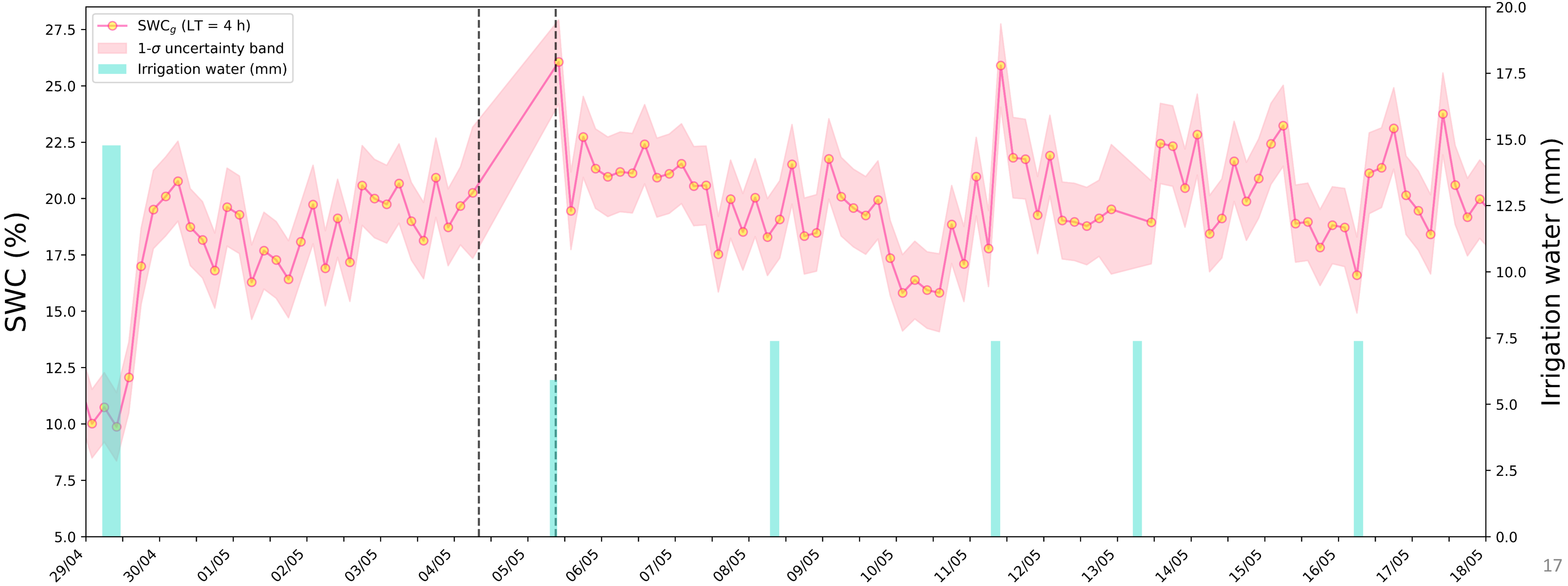
Acq. time	Median $\boldsymbol{\Delta SWC}$ (%)	Mean SWC (%)
1 h	1.50	6.72
2 h	1.19	6.68
3 h	1.07	6.72
4 h	0.98	6.71

$$\Delta \boldsymbol{SWC} = |\boldsymbol{SWC}(\boldsymbol{t} = \boldsymbol{i}) - \boldsymbol{SWC}(\boldsymbol{t} = \boldsymbol{i} + \boldsymbol{a})|$$

$$where\ a = (1,2,3,4)\ h$$

Comparison of gamma data with irrigation in the GH site

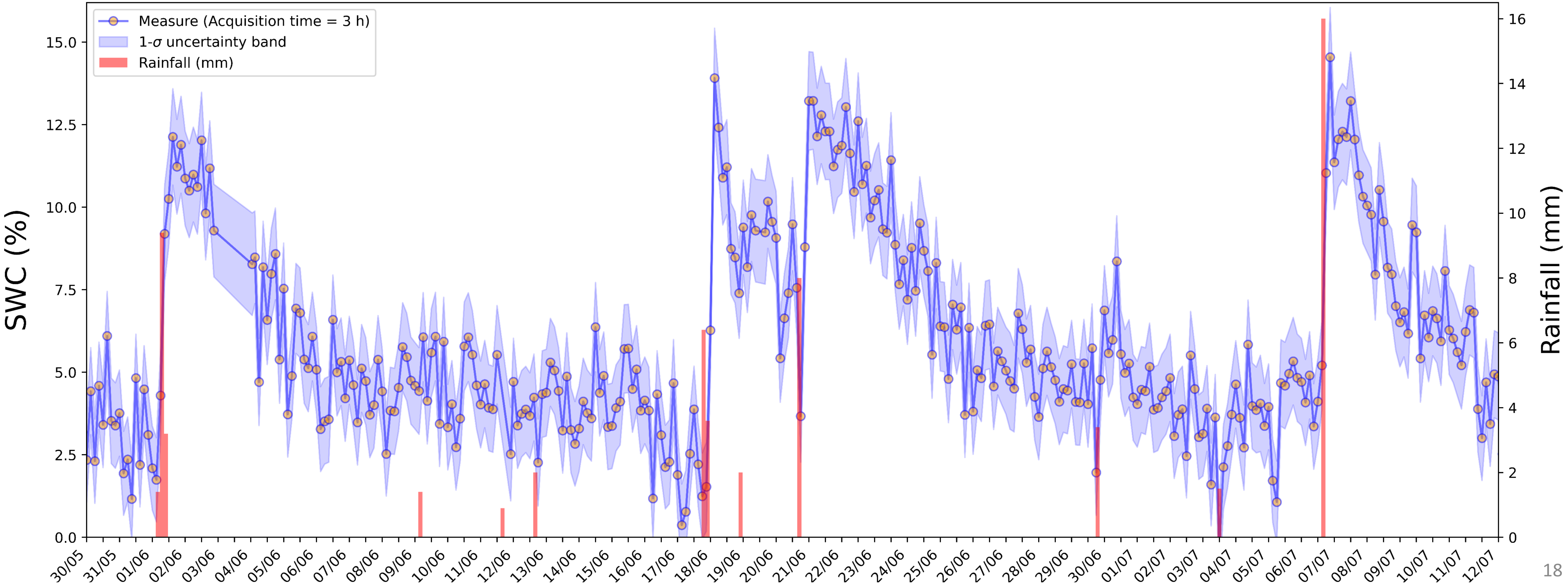
- Given that the fluctuation between two points exceeds 3σ cannot be justified as statistical fluctuations, the irrigation of **29/04**, **11/05** and **16/05** are well recognized by the gamma system while for the other events there is no absolute evidence of that.
- Therefore, due to the results presented above, it is believed that the PGRS system installed in the GH site can detect with certainty **irrigation events that exceeds 8 mm of water**.



Comparison of gamma data with rainfall in the WF site

- The rainfalls of **01/06, 17/06, 20/06, 29/06** and **06/07** are well recognized by the PGRS data while for the other events, the fluctuation is too reduced to hypothesize a rainfall event.

- Therefore it is believed that the PGRS system installed in the WF site can detect with certainty **rainfall events** that **exceeds 3 mm of water**.



Validation of the results

In order to test the performance of PGRS in SWC evaluation is reported a **comparison** of the two values of SWC obtained in the **same temporal window** with two **different methods**: PGRS (SWC^{γ}) and gravimetric measurements (SWC^{grav}).

Site	Date	Samples collected	Soil conditions	SWC^{grav} (%)	SWC^{γ} (%)
GH	28/06/2023	4	bare	(8.3 ± 0.4)	(8.1 ± 1.4)
GH	25/07/2023	4	vegetated	(19.3 ± 0.9)	(18.7 ± 1.7)
WF	21/07/2023	6	vegetated	(3.1 ± 1.6)	(3.5 ± 1.3)

Conclusions and future prospective

- The gaussian fit method allows to **reduce** the **fluctuations of the quantity ΔCPS** around 31% with respect to the trapezium method. For this reason, I developed a specific **C++ code** performing the gaussian fit running **real time on the MCA**.

- To ulteriorly reduce the fluctuations between two consecutive values of CPS_{net} it's necessary to increase the statistics by **raising the acquisition time**. The results of the analysis allowed to select an acquisition time for the GH site ($V_{detector}$ = 0.1 L) of **4 h** while for the WF site ($V_{detector}$ = 0.4 L) of **3 h**.

- In the GH site, the PGRS system can detect with sufficient accuracy **irrigation** events that exceeds **8 mm** of water, while for the WF site the PGRS system can recognize **rainfall** events that exceeds **3 mm** of water.

- The **validations measurements** of SWC performed on three soil sample of both sites revealed to be consistent with the value obtained through PGRS showing a **discrepancy** between the two values significantly **lower than 1σ**.

- Future perspective…
  - study the impact of a **wider set of crops** on the gamma signal
  - implement a **comparison system** with the data from **satellite measurements**
  - **reduce the limits** of watering events recognition.

Thanks for your attention

Michele Franceschi