# Error estimation for soil moisture measurements with cosmic-ray neutron sensing and implications for rover surveys

Jannis Jakobi[1], Johan A. Huisman[1], Martin Schrön[2], Justus Fiedler[1], Cosimo Brogi[1], Harry Vereecken[1] and Heye R. Bogena[1]

[1]Agrosphere Institute (IBG-3), Forschungszentrum Jülich GmbH, Jülich, Germany; [2]Department of Monitoring and Exploration Technologies, Helmholtz-Zentrum für Umweltforschung GmbH - UFZ, Leipzig, Germany

## Motivation

- The aboveground epithermal neutron intensity is effectively determined by surrounding hydrogen, enabling field-scale soil moisture measurements
- The uncertainty of soil moisture measurements with cosmic-ray neutron sensing (CRNS) among other sources depends on the uncertainty in poisson distributed neutron counts: decreasing soil moisture corresponds to decreasing neutron intensity and increasing uncertainty in neutron counts

→ Reduced uncertainty with more effective detectors, arrays of detectors (e.g., CRNS roving) or aggregation over long time windows (e.g., 12 or 24 h)

- We present an easy-to-apply method for assessing the soil moisture uncertainty from neutron counts, compare it to a computationally intensive Monte Carlo approach and elaborate on implications for the planning and evaluation of CRNS rover surveys

## Uncertainty from neutrons

Cosmic-ray neutrons can be converted to soil moisture via:

$$\theta_v = \varrho_{bd}\left[a_0\left(\frac{N_{cor}}{N_0}-a_1\right)^{-1} - a_2 - \theta_{off}\right]$$

Desilets et al., (2010)

$\theta_v$ = volumetric soil moisture [m³/m³]
$\varrho_{bd}$ = soil bulk density [g/cm³]
$N_{cor}$ = pressure, humidity and incoming flux corrected neutron counts [cts]
$N_0$ = calibration parameter, usually calibrated with reference soil moisture [cts]
$\theta_{off}$ = constant water pools (e.g., soil organic carbon, lattice water) [g/g]
$a_i$ = fitting paremetes obtained by Desilets et al. (2010)

The uncertainty in neutron counts is defined by $\sqrt{N}$ and for error estimation must be propagated to corrected neutron counts:

$$\sigma_N = s\sqrt{N}$$

$s$ = prodcut of corrections for pressure, humidity and incoming flux
$\sigma_N$ = uncertainty in corrected neutron counts

We used an **analytical Taylor expansion approach** up to 3rd polynomial order, considering 6 central moments in the uncertainty distribution (Mekid and Vaja, 2008). Because the neutron count detection statistics converges to a symmetric Gaussian normal distribution, only the 2nd, 4th and 6th moments are relevant:

$$\sigma_{\theta_v} = \varrho_{bd}\frac{a_0 N_0}{(N-a_1 N_0)^4}\sqrt{(N-a_1N_0)^4 + 8\sigma_N{}^2(N-a_1N_0)^2 + 15\sigma_N{}^4}$$

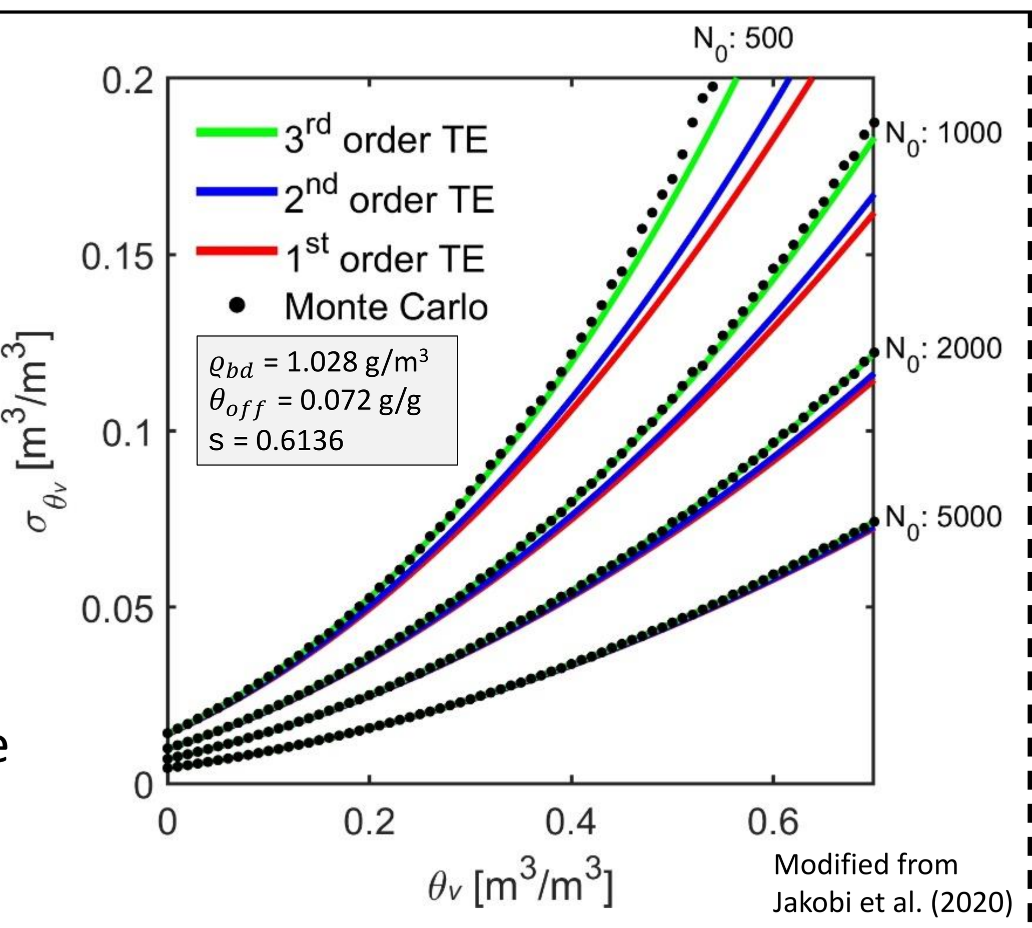
$\sigma_{\theta_v}$ = volumetric soil moisture uncertainty from neutron counts [m³/m³]

For evaluation we used a **Monte Carlo approach**:

1. Neutron counts for 0.0 – 0.7 m³/m³ soil moisture ▶
2. Recalculate to raw neutron counts: $\frac{1}{s}N_{cor}$ ▶
3. Generate large sets of draws from poisson distribution ($N_{out}$) ▼
4. Rescale to corrected neutron counts: $sN_{out}$ ◀
5. Convert to soil moisture (Desilets et al., 2010) ◀
6. Obtain the standard deviation

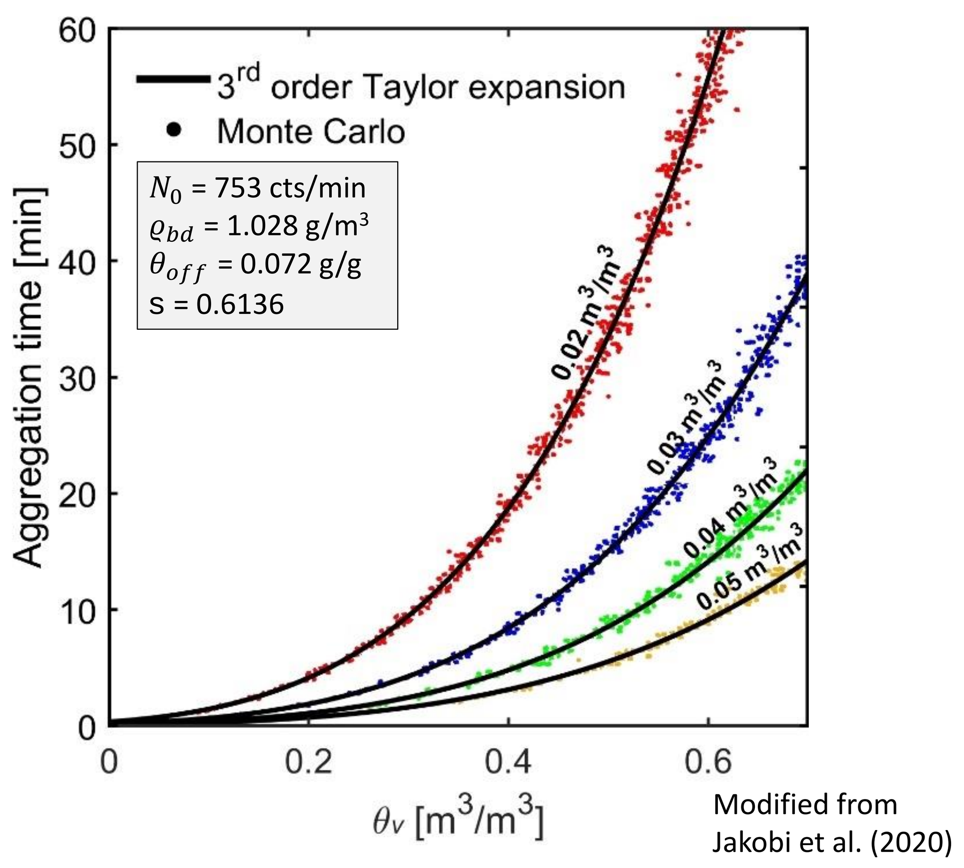
## Method comparison and application

- As expected increasing soil moisture leads to increasing uncertainty in soil moisture estimation
- Aggregation (increasing $N_0$) reduces the uncertainty
- Below $N_0$ = 1000 slight deviations with high water content due to the asymptote at $a_1N_0$



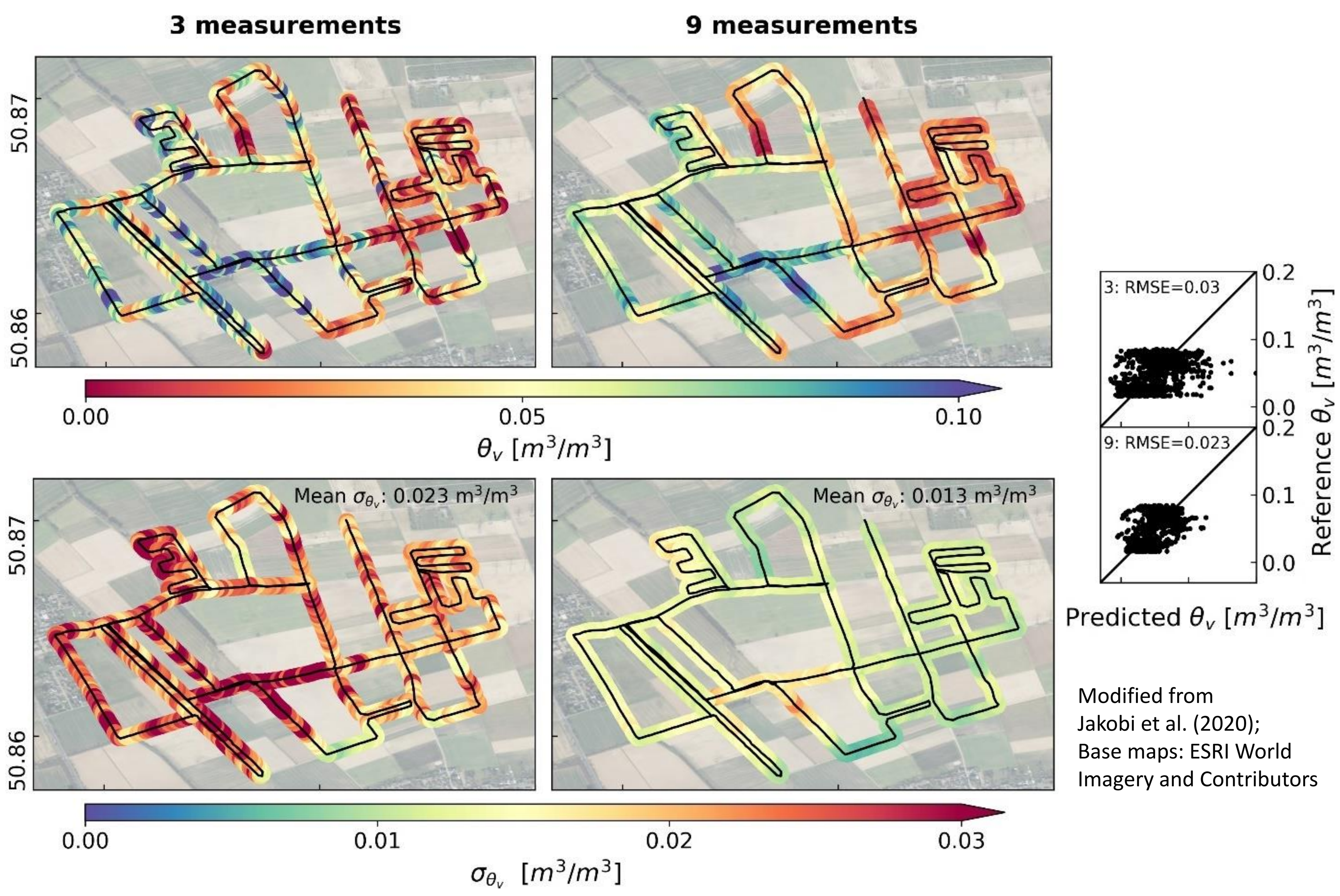
Modified from Jakobi et al. (2020)

- With the Jülich CRNS rover and soil moistures below 0.4 m³/m³ an aggregation time up to 10 min is necessary to achieve an uncertainty below 0.03 m³/m³
- With lower uncertainty requirements the necessary aggregation time can be drastically reduced



Modified from Jakobi et al. (2020)

Example of the influence of **aggregation** on the measurement uncertainty



Modified from Jakobi et al. (2020); Base maps: ESRI World Imagery and Contributors

- Clear accuracy improvement due to aggregation

→ Decreased RMSE and decreased soil moisture uncertainty from neutrons

- Additional sources of uncertainty are not considered here and explain the remaining RMSE:

→ e.g., uncertainties in soil bulk density, vegetation, roads, inconsistencies between in-situ and CRNS measurements

## Conclusions

- Measurement uncertainty from neutron counts can be easily estimated with the proposed approach
- With appropriate aggregation the uncertaitny can be reduced significantly
- The aggregation length for a roving experiment needs to be carefully selected based on:

→ rover capabilites; site characterisics; accuracy requirements of the user

Jakobi, J. C., J. A. Huisman, Schrön, M., Fiedler, J. E., Brogi, C., Vereecken, H. and Bogena, H. R. (accepted). Error estimation for soil moisture measurements with cosmic ray neutron sensing and implications for rover surveys. In: Frontiers in Water