Novel Method for Calibrating Actively Heated Fiber Optic (AHFO) Soil Moisture in a Heterogeneous Field: From Theory to Field Application

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Measuring soil moisture content

Actively heated

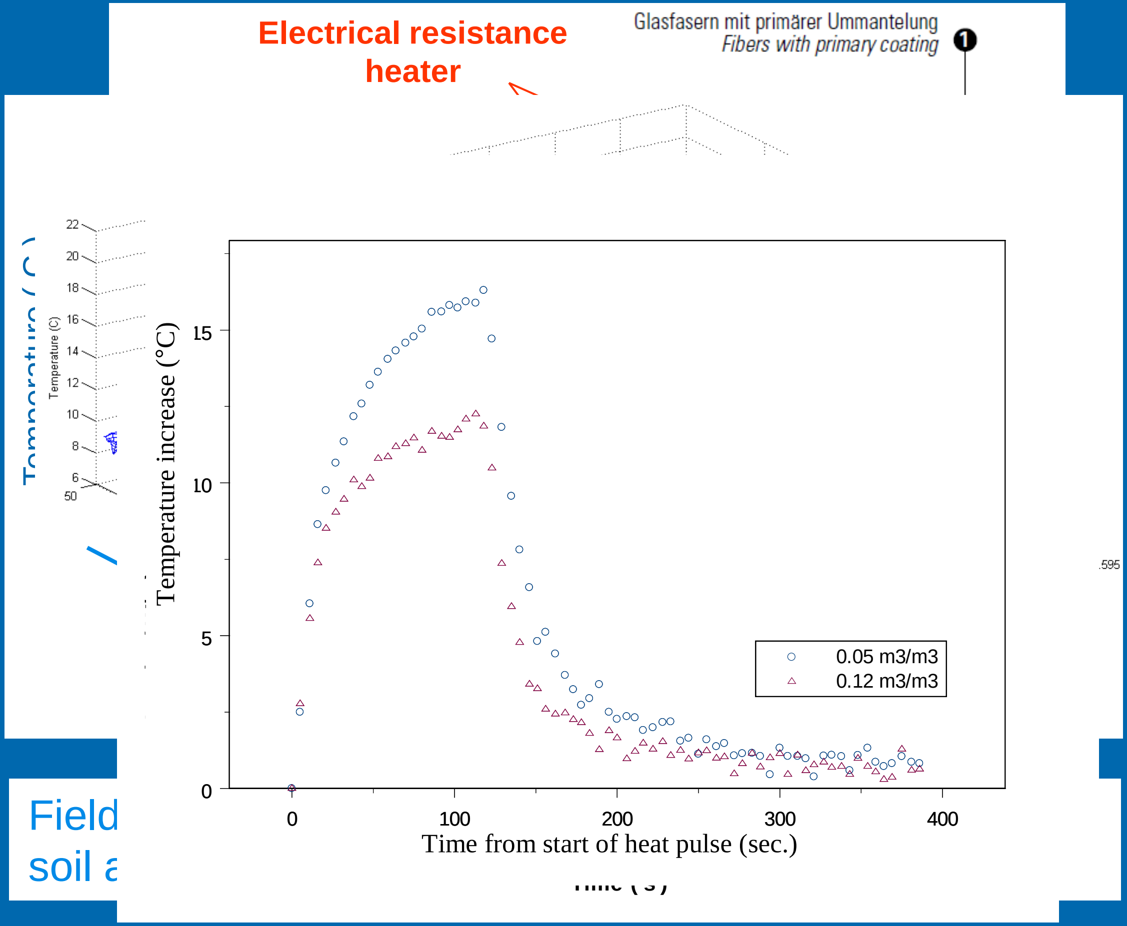
Heat injected in soil along fiber optic cable

↓

DTS reads temperature changes during heat pulse along fiber optic cable

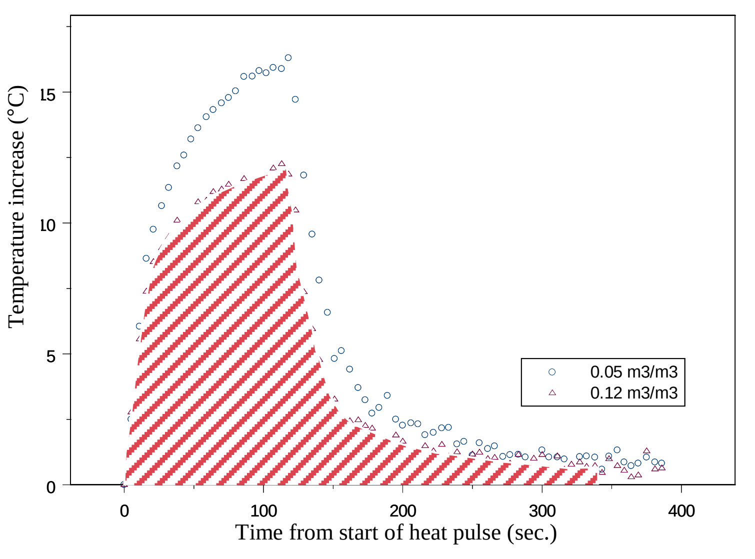
↓

Soil water content inferred from thermal response of soil to the heat pulse



Heat Pulse Interpretation:
The Integral Method

$$T_{cum} = \int_{t_0}^{t_j} \Delta T \, dt$$



T_{cum}	is the cumulative temperature increase
t_0	is the time to start of a heat pulse
t_j	is the total time of integration
ΔT	is the temperature increase over ambient temperature.

Calibration approaches so far

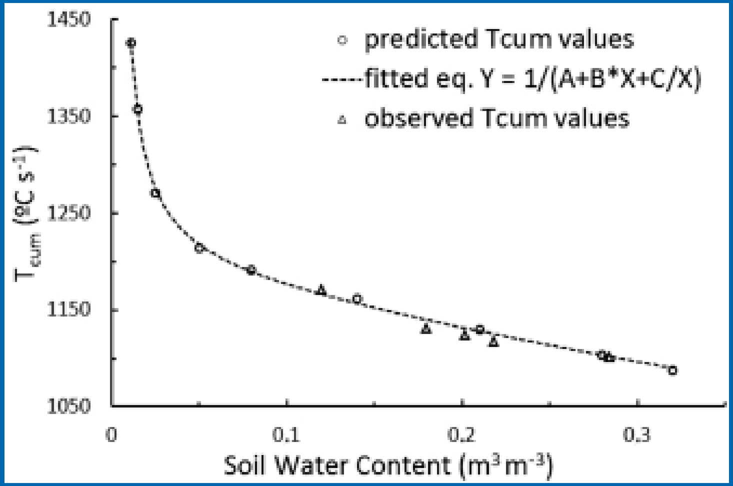
Typical AHFO calibration approaches try to generate empirical calibration curve:

- **Modeled** calibration curves from measured thermal properties. (Buelga et al. 2016)
- **Laboratory generated** calibration curves. (Sayde et al., 2010; 2015)
- **Field generated** calibration curves from independent in-situ measurements of soil moisture contents. (Loheid et al. 2014) .

Collect non-disturbed samples

Measure thermal properties in the lab

Generate calibration curves using heat transfer models



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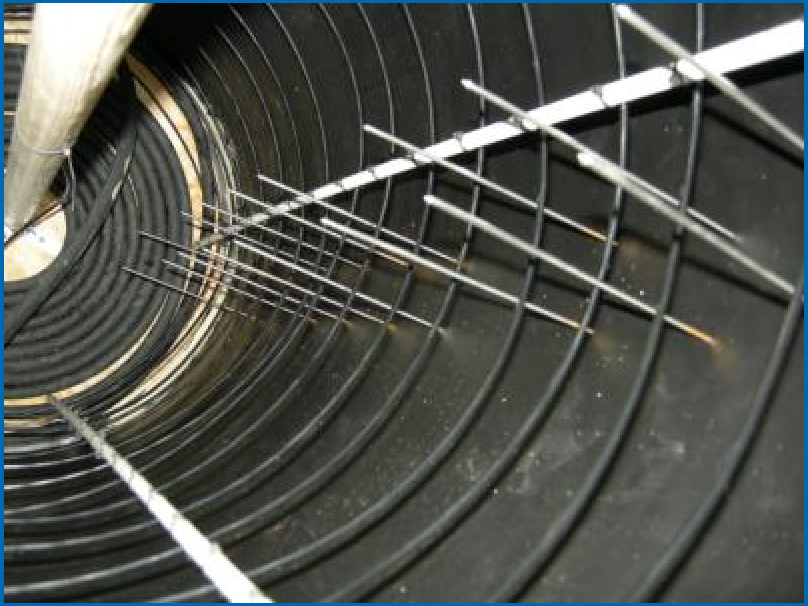

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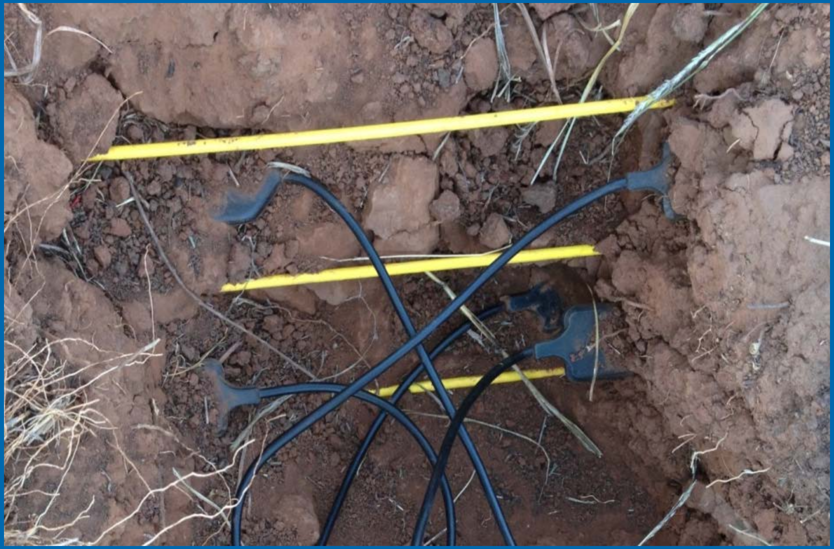
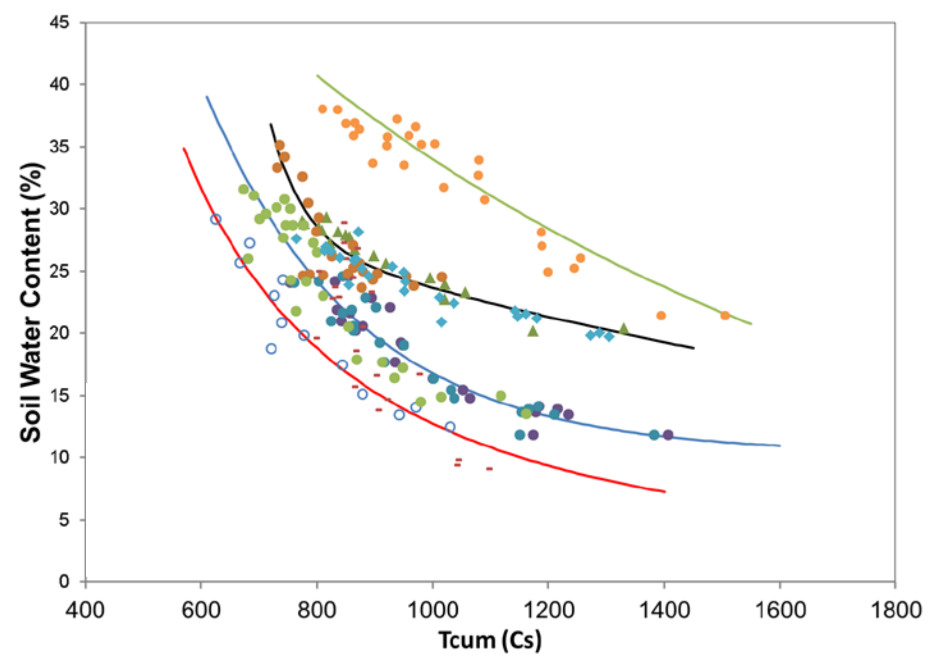
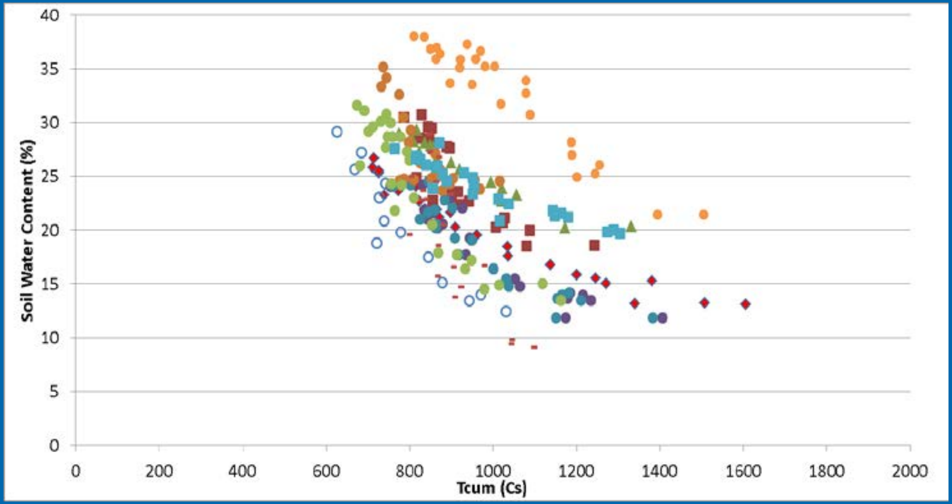



Soil Water Content (%)
0
5
10
15
20
25
30
35
40
45
400
600
800
1000
1200
1400
1600
1800
Tcum (Cs)

Calibration Challenges

Limited adaptability so far:

- Empirical calibration curves.



- A calibration curve has to be developed for each soil conditions.

- Can be difficult to obtain, unpractical and expensive.

- Difficult to apply in a complex field where large variability in the background soil thermal properties is observed.

Novel Distributed Calibration Model

- Kersten function (*Ke*) can be found at any location and for the whole soil moisture range from *Tcum* at dry and at saturation:

$$Ke = \frac{Tcum_{sat}^{b}}{Tcum^{b}}\left[\frac{Tcum_{dry}^{b} - Tcum^{b}}{Tcum_{dry}^{b} - Tcum_{sat}^{b}}\right]$$

- *b*, the shape coefficient, is particular to probe
- Degree of saturation (*Sr*) can be computed from published models relating *Ke* to *Sr*. e.g. Lu et al. (2007):

$$Ke = \exp\left\{\propto\left[1 - S_r^{(\propto-1.33)}\right]\right\}$$

- *Sr* = degree of saturation (-),α = 0.96 for coarse soils, α = 0.27 for fine soils

Numerical Validation

- *Tcum* is calculated from the solution of the heat conduction equation for a heat pulse of duration t_o (s) applied to a line source, such as:
- $$\Delta \mathrm{T} = \frac{q'}{4\pi\lambda} Ei\left(\frac{r^2}{4\kappa t}\right) \qquad \text{for } 0 < t \leq t_0$$
- *q'*: energy input (J m^{-1} s^{-1}), ***λ***: thermal conductivity of soil (W m^{-1} °C^{-1}), ***K***: thermal diffusivity of soil (m^2 s^{-1}), *r*: probe radius (m), *t*: time from start of heating (s).

Simulating Spatial variability

- Monte-Carlo simulation:

$$\lambda_s \sim U(2, 7) \qquad n \sim U(0.3, 0.65)$$

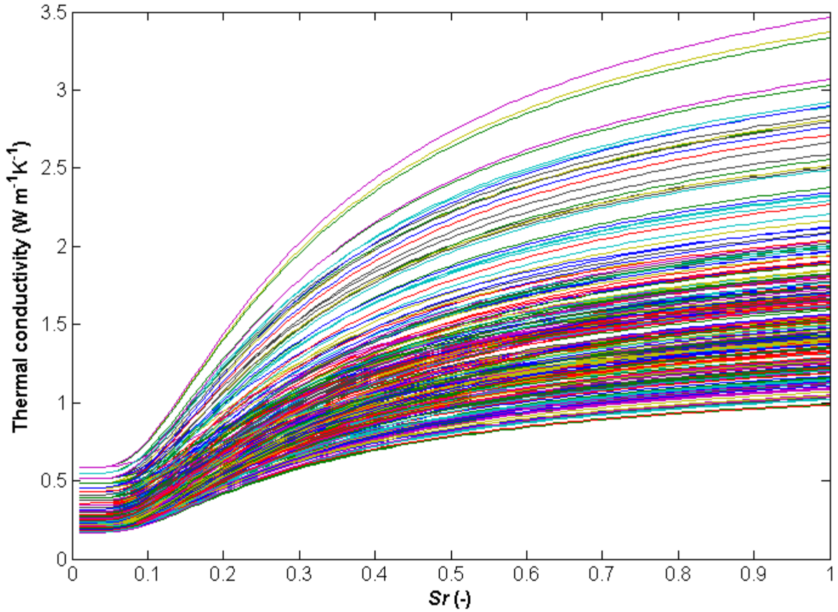
Common soil minerals

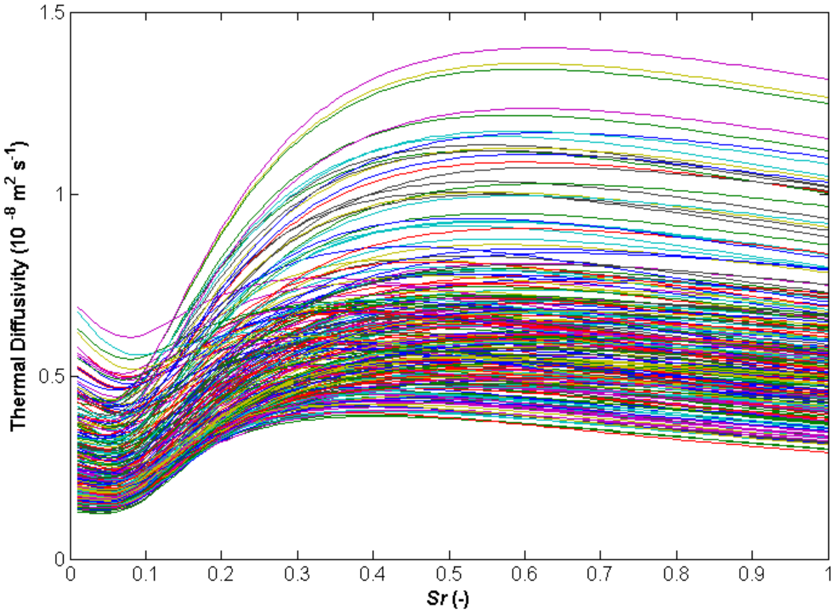
Quartz

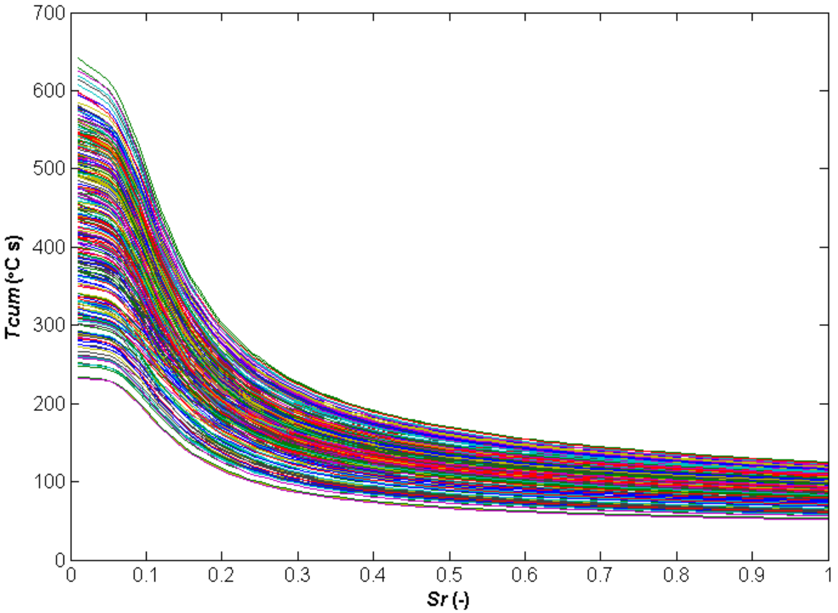
Sandy soil

Clay

- Calculate λ and K $\longrightarrow$ *Tcum*
  for full range of *Sr*


Thermal conductivity (W m^{-1}K^{-1})
0
0.5
1
1.5
2
2.5
3
3.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Sr (-)


Thermal Diffusivity (10^{-8} m^{2} s^{-1})
0
0.5
1
1.5
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Sr (-)


Tcum (°C s)
0
100
200
300
400
500
600
700
0
0.1
0.2
0.3
0.4
0.5
0.6
0.7
0.8
0.9
1
Sr (-)

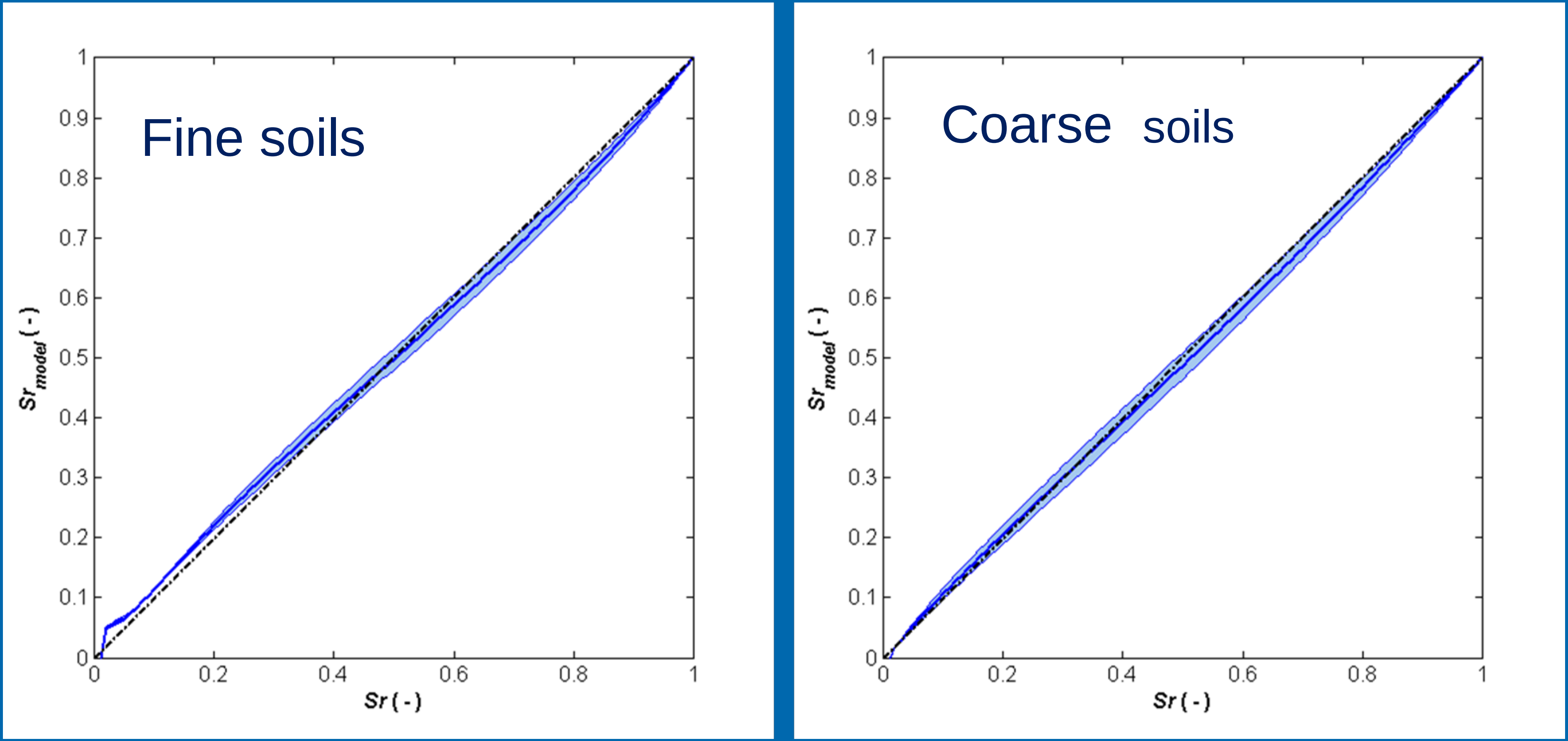
Calibration/Validation

- Tcum was calculated from published heat conductivity model for different *Sr*

- Now calculate *Sr* from *Tcum* using The new calibration model

- Non-linear least square was employed to find b=0.65 that best fit modeled to synthetic *Sr*

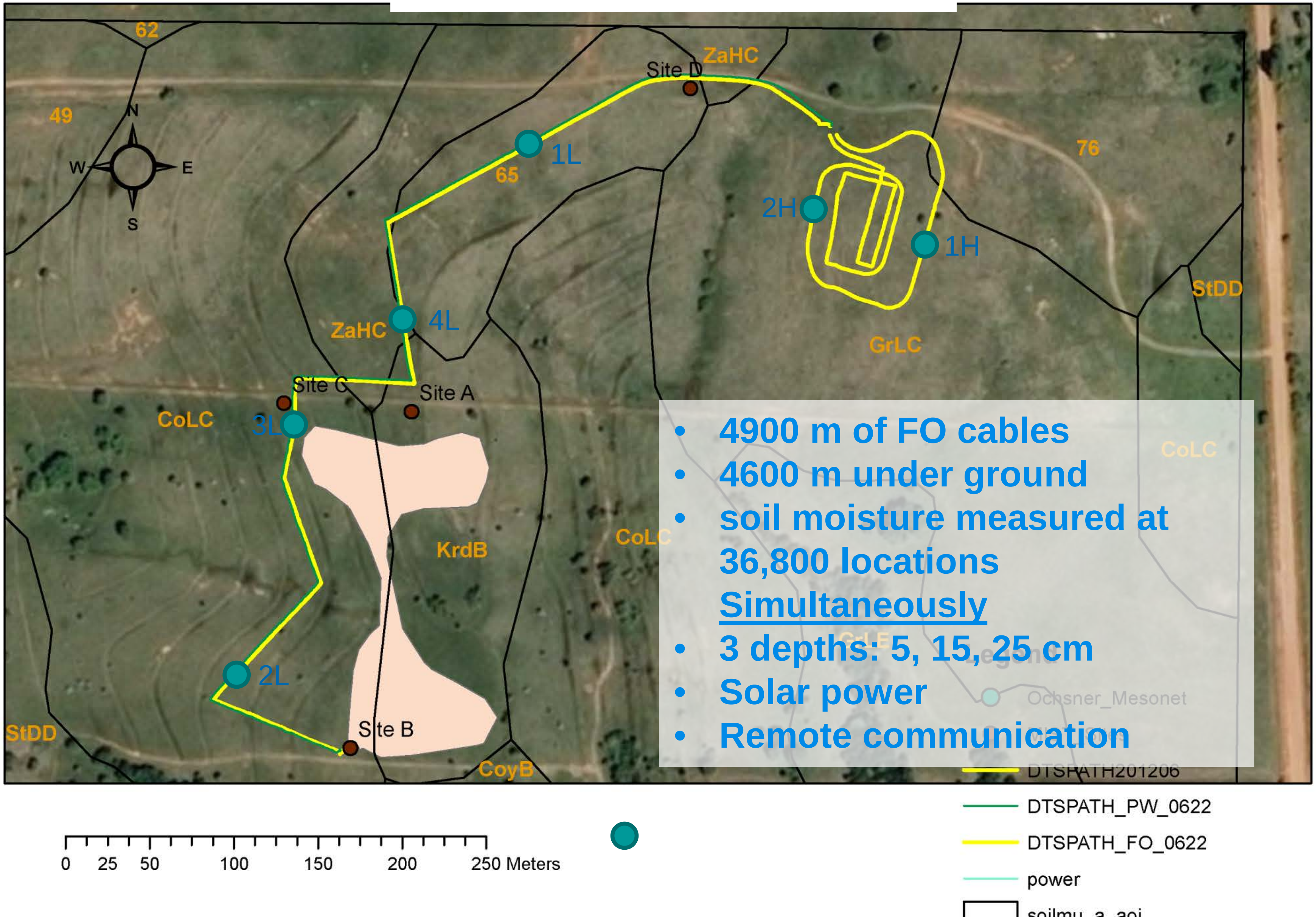
Results



Synthetic (Sr) vs modeled (Sr_{model}) degree of saturation (blue line). The shaded areas represent 1 standard deviation in Sr_{model}

CV=1.5 %

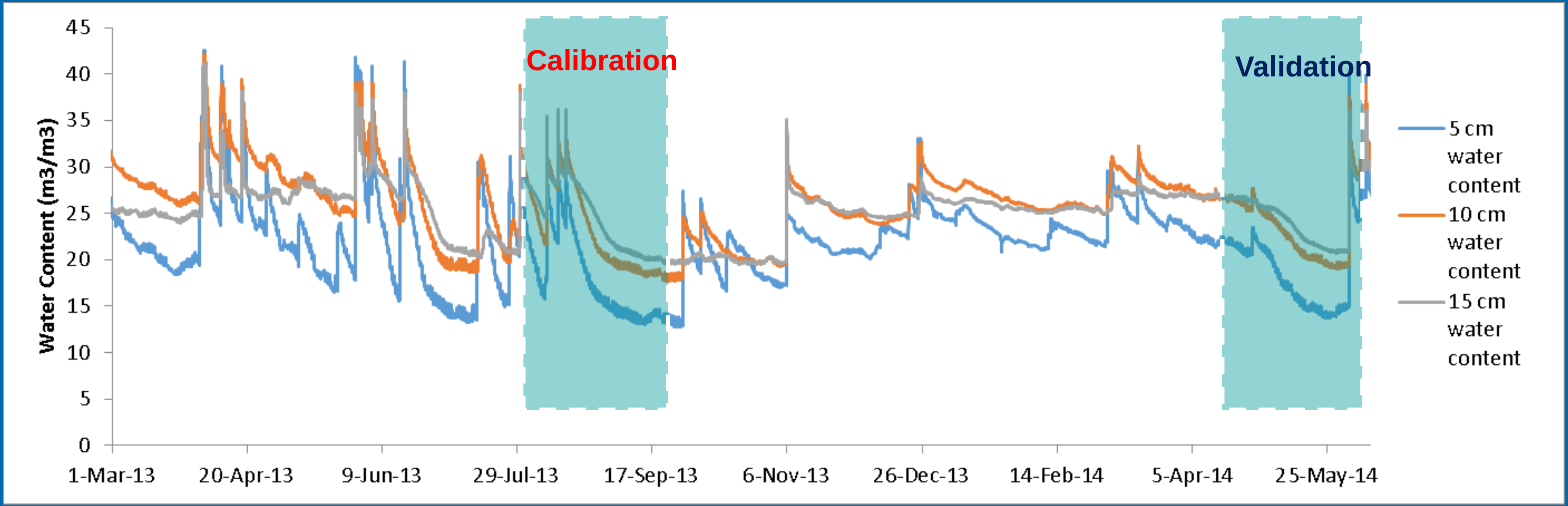
Field Validation



- **4900 m of FO cables**
- **4600 m under ground**
- **soil moisture measured at 36,800 locations <u>Simultaneously</u>**
- **3 depths: 5, 15, 25 cm**
- **Solar power**
- **Remote communication**

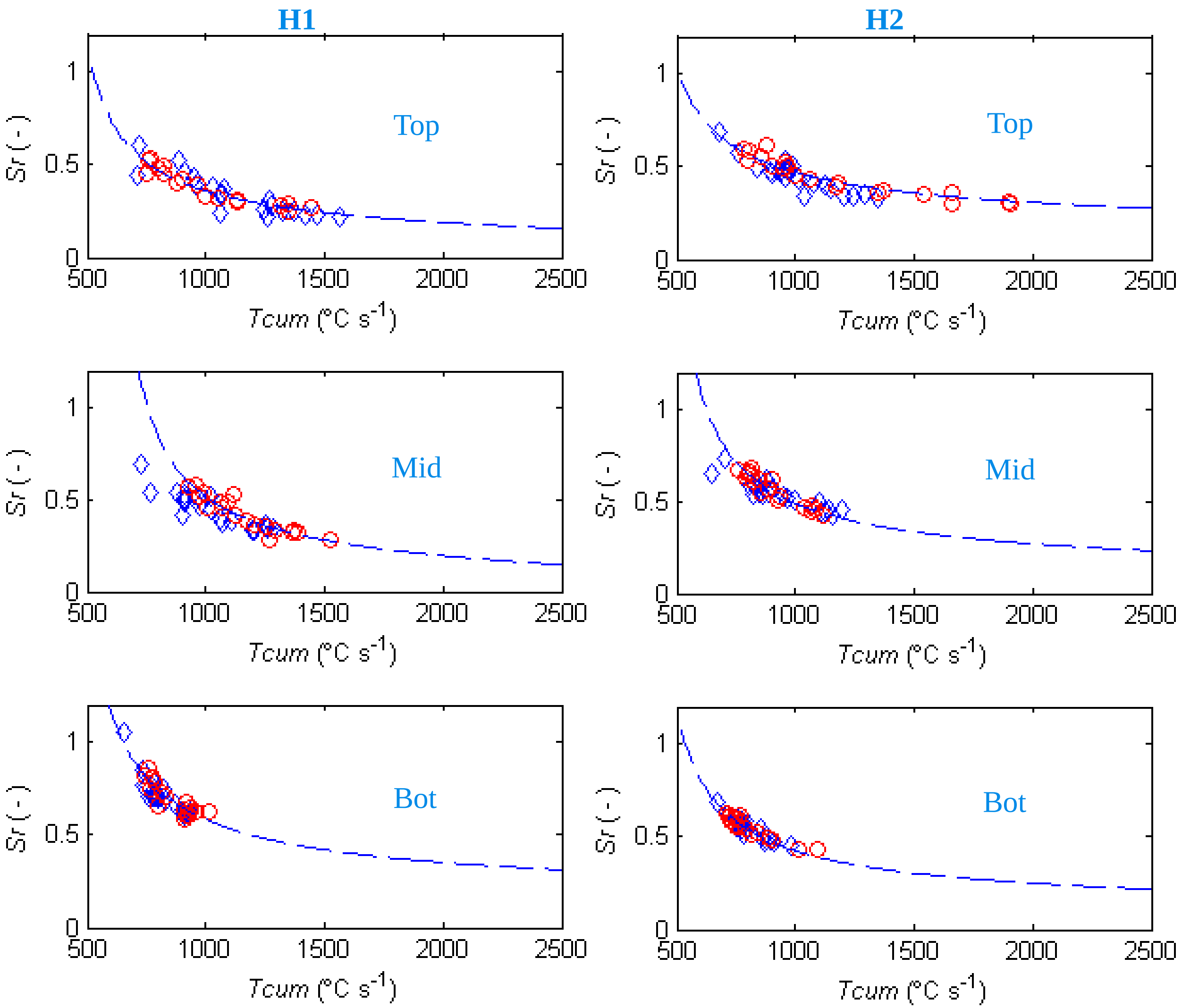
NASA DTS MOISST Project

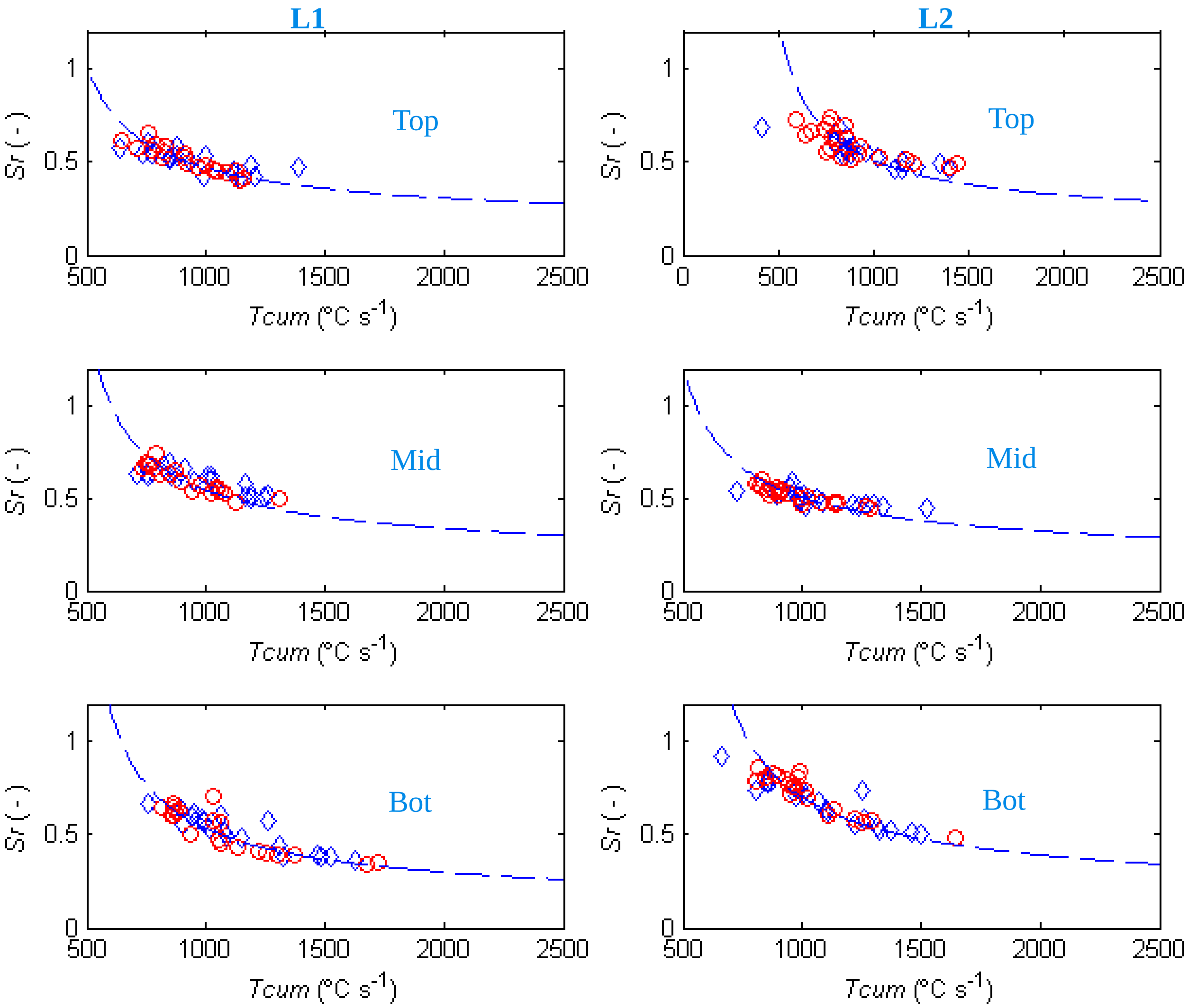
Field Validation

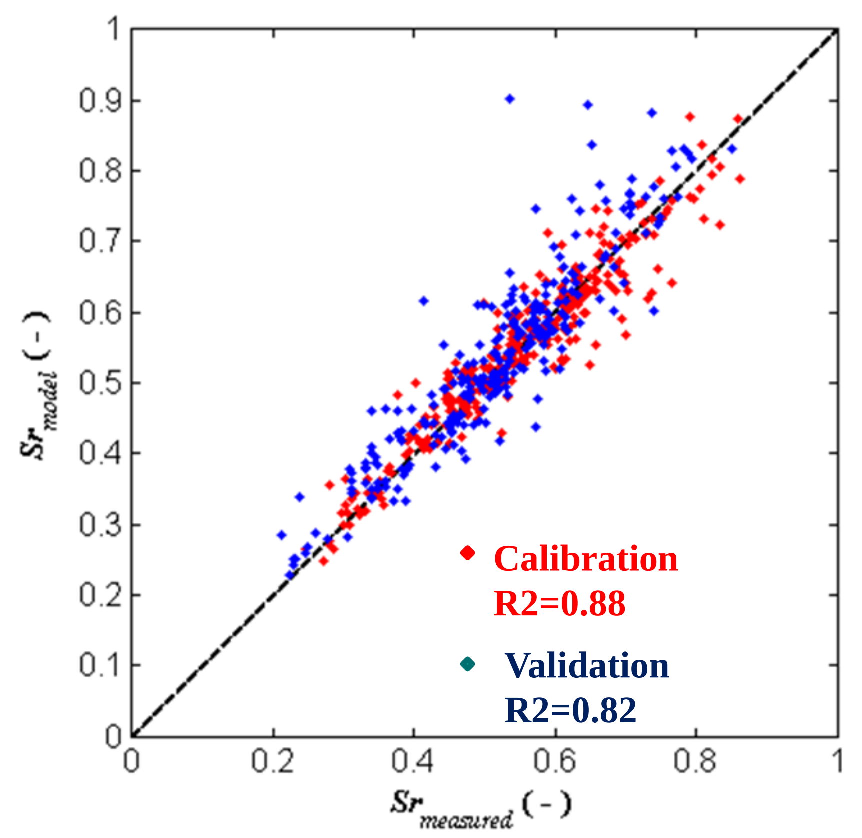


Model Calibration

- Calibration: August, 3 to September, 5.
- Validation: April, 25 to June, 7.
- Least Square fitting was employed to find best fit for Tcum at saturation and dry conditions and for b.
- *b*=0.25, provides excellent fit for all locations.


H1
H2
Top
Mid
Bot
Sr (-)
0
0.5
1
500
1000
1500
2000
2500
Tcum (°C s-1)


L1
L2
Top
Mid
Bot
Sr (-)
1
0.5
0
0
500
1000
1500
2000
2500
Tcum (°C s-1)


1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Sr_{model} (-)
0
0.2
0.4
0.6
0.8
1
$Sr_{measured}$ (-)
◆ Calibration
R2=0.88
◆ Validation
R2=0.82

Conclusions

- In theory, the new calibration model works for wide range of soil thermal properties. Very promising field results.
- Only 2 inputs are needed: *Tcum* at saturation and *Tcum* at dry conditions.
- *Tcum* at saturation measured after high precipitation events.
- Additional work needed to better estimate $Tcum_{dry}$ especially for fine-textured soils:
  - Incorporating Passive DTS data: adaptive Particle Batch Smoothing algorithm and Hydrus 1D modeling to reveal soil thermal properties (Dong et al., 2016)

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