Towards reliable large scale soil water content estimation: GPR for measuring soil moisture in the Urumqi region

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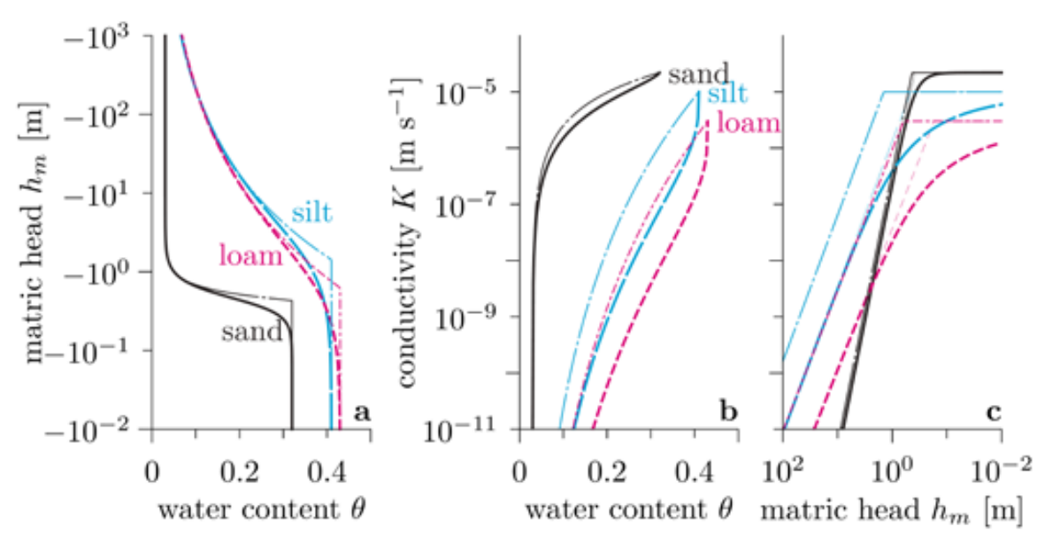
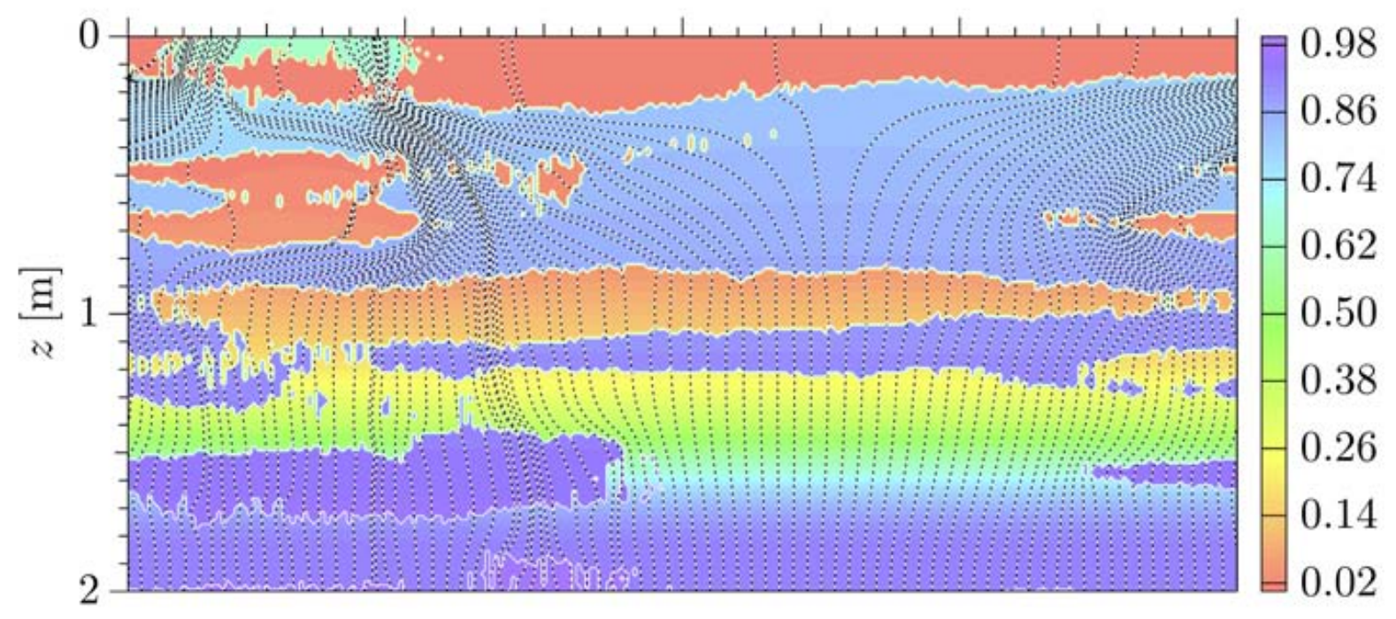
1. The origin of the challenge - a soil physicist‘s view



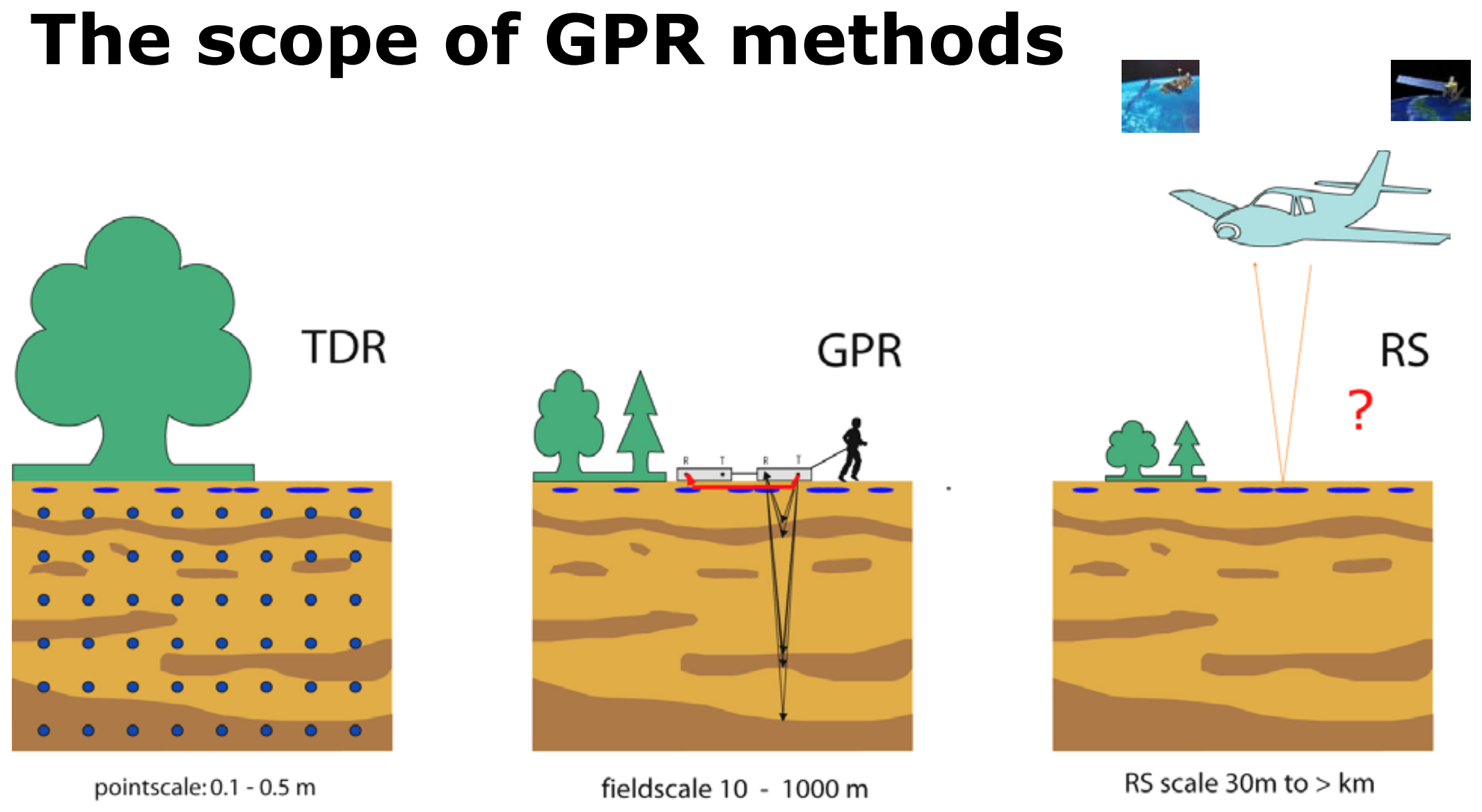
Characteristic soil hydraulic parameters for typical soil textures



Evaporative flux from a heterogeneous soil profile with a coarse textured top layer. [1]

- Governing soil water redistribution, highly non-linear small scale soil properties impede reliable large scale soil moisture estimation
- For example, soil hydraulic conductivity varies several orders of magnitude with water content
- A thin layer of dry coarse textured medium can act as a capillary barrier, potentially harboring a complex soil profile below, which may not be accessible to remote sensing methods

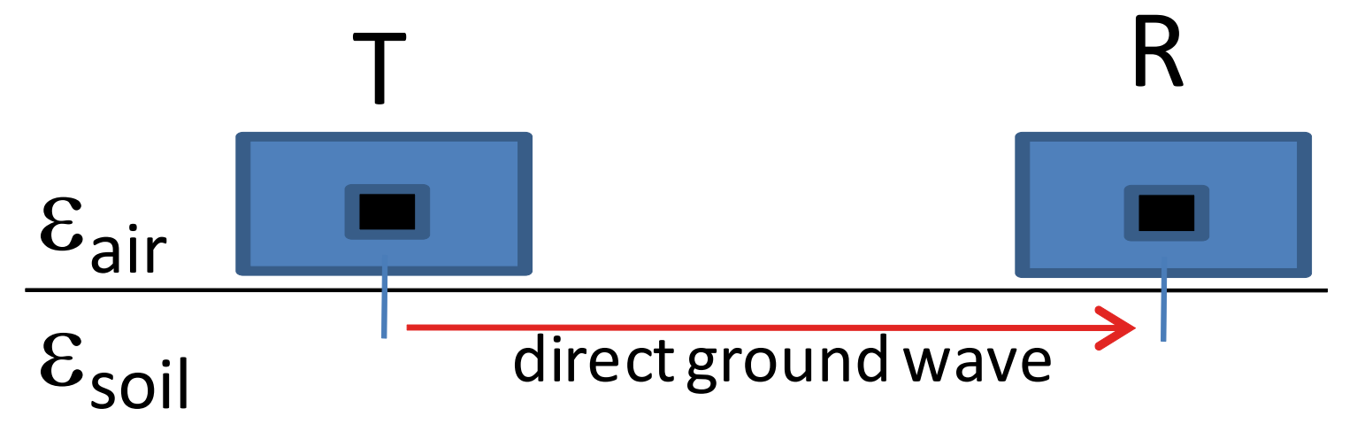
2. The scope of GPR methods



TDR: Time Domain Reflectometry
GPR: Ground-Penetrating Radar
RS: Remote Sensing

- Extending exact point-scale measurement methods of soil water content to the field scale
- Providing ground truth for medium to large scale albeit less accurate remote sensing methods

3. GPR ground wave evaluation



$$t_{GW} = \frac{a\sqrt{\varepsilon_c}}{c_0}$$

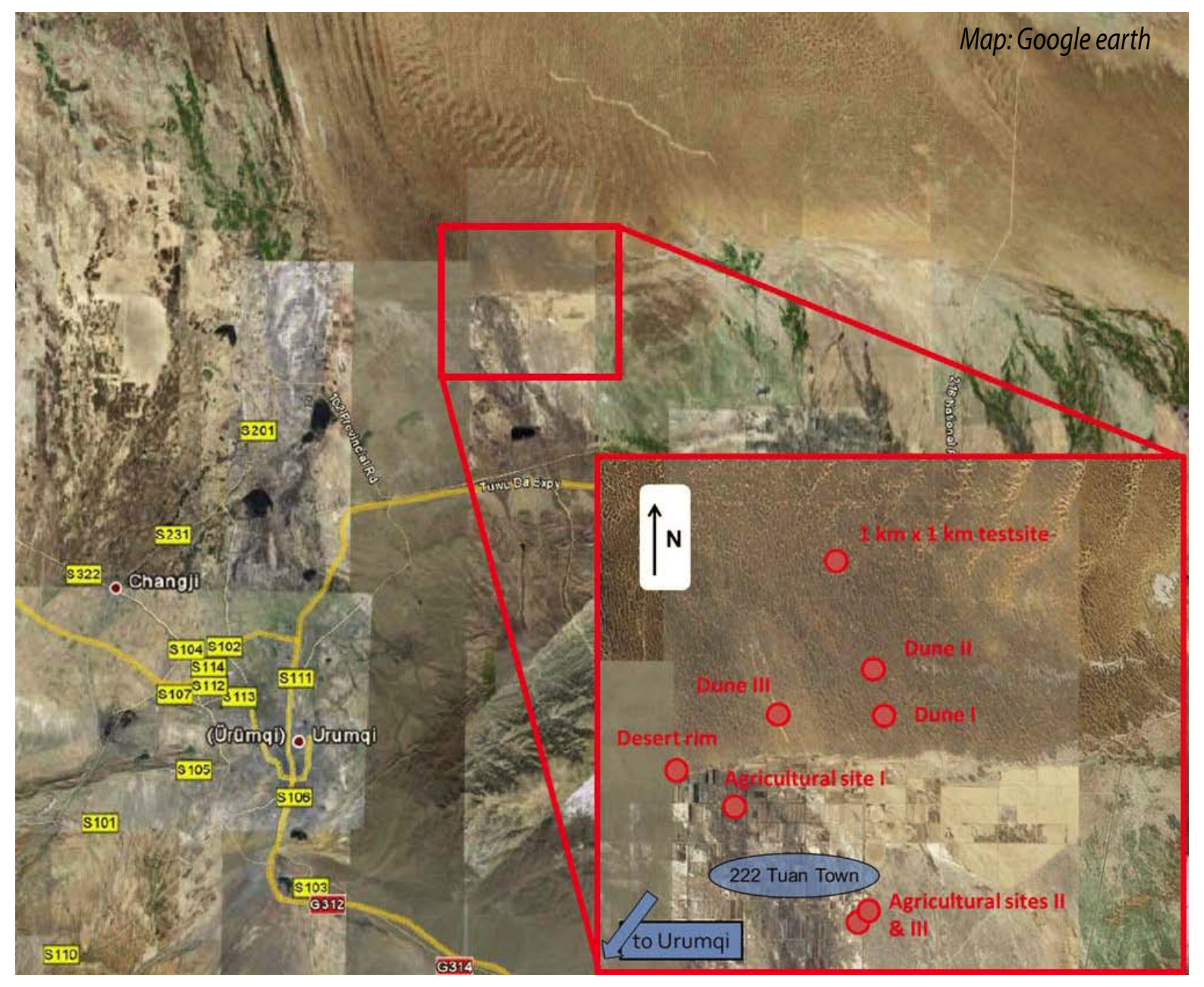
- **Ray approach**: Measuring the travel time t_{GW} from transmitter (T) to receiver (R) allows calculating the bulk dielectric permittivity ε_c from the antenna separation a and the free space wave velocity c_0, e.g. [2-4].
- **Water content values** are calculated from the inverted dielectric permittivities using a dielectric mixing model (CRIM, e.g. [5]):

$$\theta = \frac{\sqrt{\varepsilon_c} - \sqrt{\varepsilon_s} - \phi\left(1 - \sqrt{\varepsilon_s}\right)}{\sqrt{\varepsilon_w} - 1}$$

ε_s = relative permittivity of soil matrix
ε_w = relative permittivity of water
ϕ = soil porosity

4. The setting

- **Location:** 70 km to the Northeast of the city of Urumqi, Xinjiang province, Northwestern China, north of the Bogda mountain range, at only about 400 m above sea-level
- **Characteristics:** Intensively irrigated agriculturally used lands and **sparsely vegetated** onsets of the Gurbantüngüt Desert. 97% of the entire desert area occupied by fixed and semi-fixed sand dunes, vegetation coverage of 40~50% and 15~25% respectively; the study area is representative for about 30% of the region, depending on the season.
- **Timing:** just after snow melt in April 2010

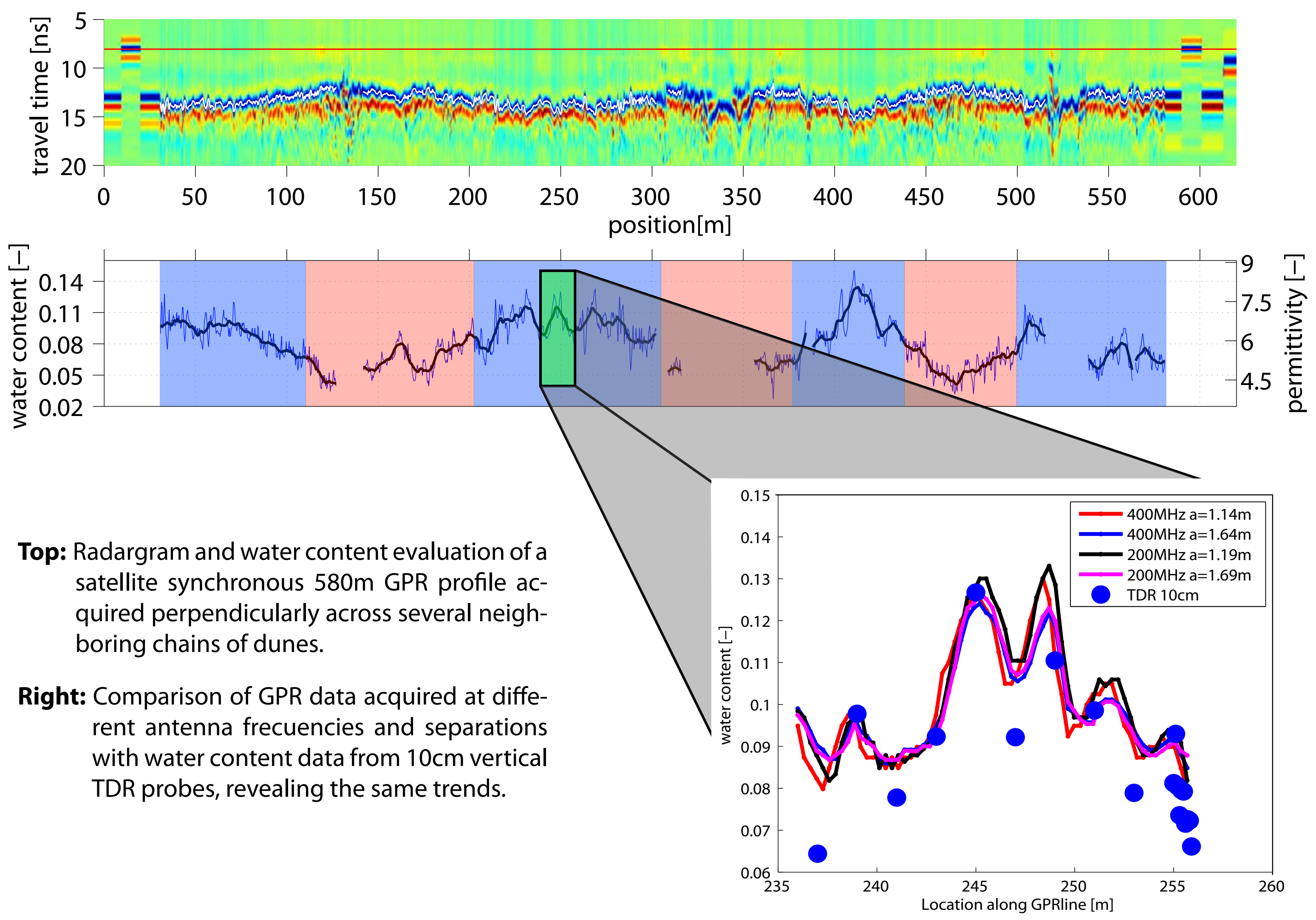


5. The subsurface

- **Top soil**: almost uniform sandy texture (USDA soil classification), relatively high soil moisture contents, due to infiltrated water from melted snow.
- **infiltration front** down to depths between 0.5 m and 1 m
- **Soil below**: uniform dry sandy texture.

6. Extending point measurements to the field scale:

Ground truth profiles extending several hundred meters



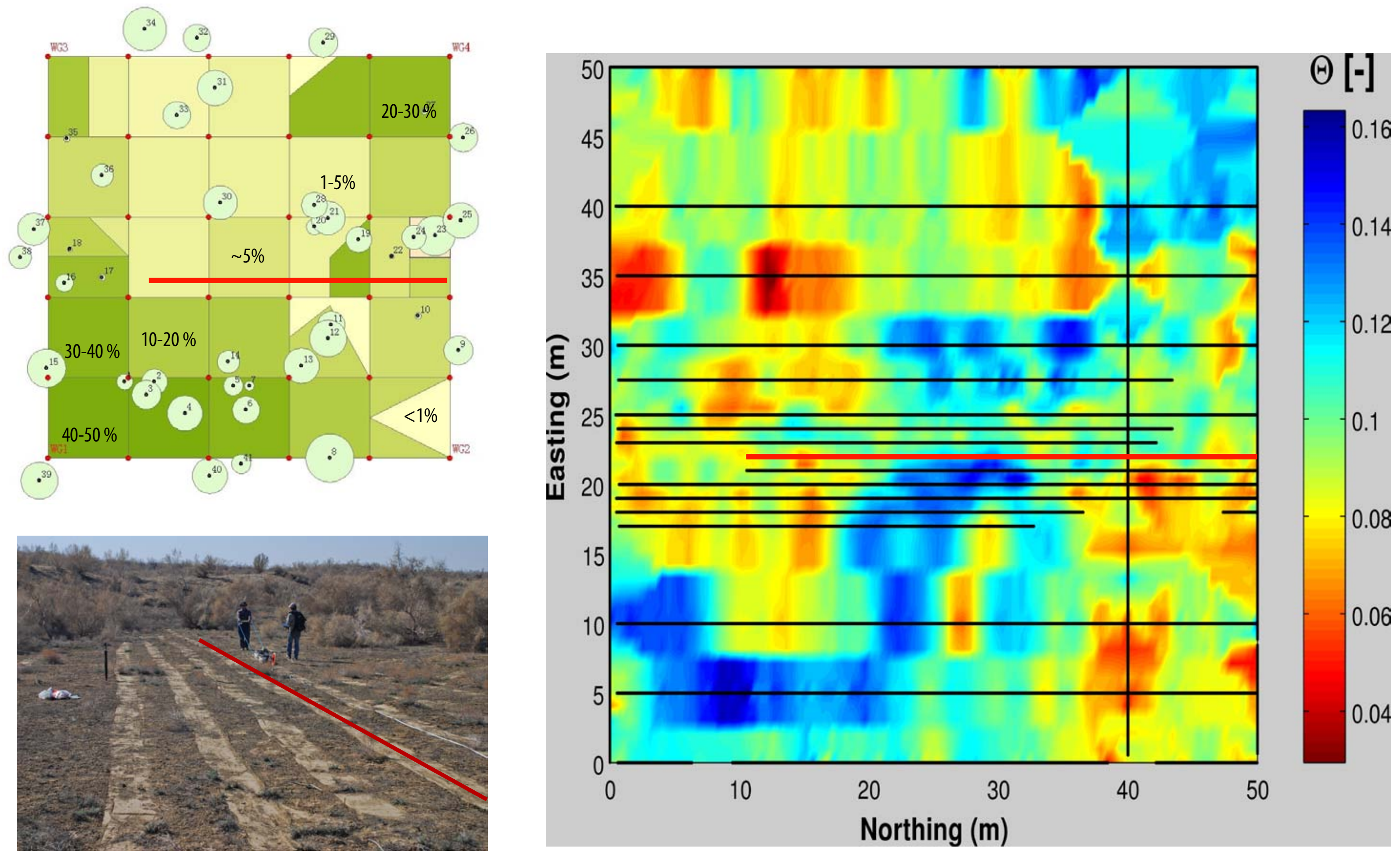
Top: Radargram and water content evaluation of a satellite synchronous 580m GPR profile acquired perpendicularly across several neighboring chains of dunes.

Right: Comparison of GPR data acquired at different antenna frecuencies and separations with water content data from 10cm vertical TDR probes, revealing the same trends.

- Ground truth measurement for remote sensing across several neighboring chains of dunes
- Inset: GPR ground wave data are a stable proxy for soil moisture content
- For the here considered profile:
  - **Topography exerts the dominant control** on the soil moisture distribution at scales of several ten to hundreds of meters. GPR evaluation yields **two distinct soil moisture regimes**, associated with topography changes (“dune-top“, marked in red, „dune-base“, marked in blue).
  - Simultaneously, **small scale variations** are resolved, e.g. for geostatistical evaluation.

7. Assessing spatial heterogeneity:

High spatial resolution within an ASAR pixel sized area



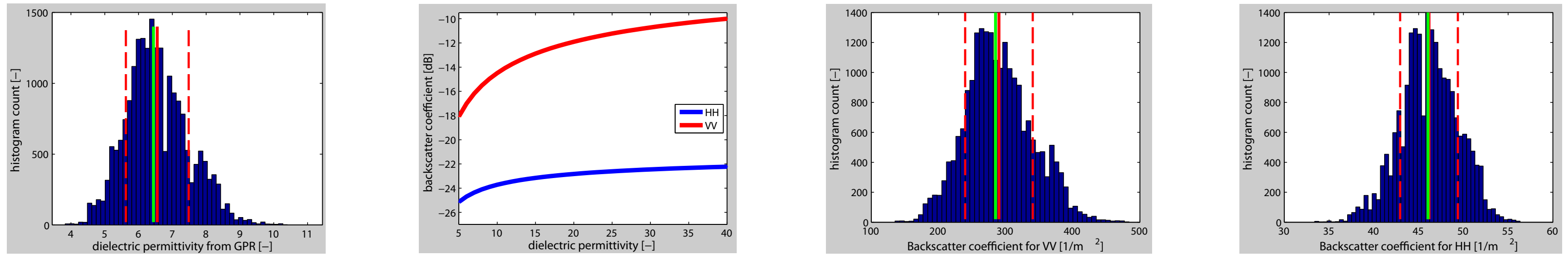
Right: 50 x 50 m ASAR pixel sized measurement. The locations of measured GPR profiles are marked with black lines.
Top left: Vegetation cover in the measured pixel.
Bottom left: Overview of the most densely sampled central area of the measurement plot, view is to the North.

- GPR for assessing sub-pixel scale spatial heterogeneity in soil moisture content, here:
  - Seemingly dry soil surface (top 3-5 cm) conceals a quite heterogeneous subsurface soil moisture pattern
  - These heterogeneous structures cannot be easily associated with surface properties (e.g. vegetation coverage)

8. Conclusions

- GPR ground wave measurements provide a **stable proxy for soil moisture**, as verifiable through TDR measurements and soil profiling
- Both **large scale characteristics** and **small scale heterogeneity** can be assessed simultaneously, allowing for **efficient ground truth** for remote sensing methods
- GPR can give access to information that may not be accessible directly to current remote sensing methods

9. For Discussion



How beneficial is detailed knowledge about small scale properties of the soil moisture field for current retrieval algorithms?

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Acknowledgements

We thank all the helping hands during data taking and evaluation, especially Wang Qianfeng, Li Guangyu, Dou Dongming, our driver Mr. Zhou for his patience, all other involved colleagues at XIEG and IUP and the ever friendly staff of the XIEG Fukang desert research station for all their help. The prolific discussions with Ute Wollschläger (UFZ Leipzig) are much appreciated.
The financing through the BMBF future megacities project in the framework of RECAST Urumqi is gratefully acknowledged.