On the Reliability of Current GPR Ground Wave Methods for Determining Near-Surface Water Contents

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***Abstract*—We explore the stability of the Ground-Penetrating Radar (GPR) ground wave signal and its applicability for measuring near-surface water contents along a 0.6 km long measurement line, crossing several vegetated sand dunes at a semi-desert site in Northwestern China. We find that the direct ground wave signal is a stable proxy for measuring near-surface soil moisture. However, the absolute water content may be difficult to establish without additional auxiliary information (e.g. through TDR point measurements). This is mainly due to limitations of the current feature-to-feature evaluation of the air- and ground wave wavelets.**

***Index Terms*—Ground-Penetrating Radar, Surface GPR, Ground Wave, Near-Surface Soil Moisture, Volumetric Water Content, Semi-Arid, Sand Dunes.**

I. Introduction

Fast and accurate determination of soil water content is a critical issue in many fields of Earth sciences. For modeling of land surface processes, as well as for regional climate models and hazard prediction, precise understanding of soil water content variations at relevant scales remains an important issue (e.g. [1], [2], [3]). GPR has been repeatedly applied for measuring approximate near-surface water content distributions throughout the last decade (e.g. [4], [5], [6], [7]).

However, as has for example been shown by [8], finding a reliable quantitative relationship based on simple travel time evaluations can be difficult. Among others, interferences with various reflected and refracted signals can make it next to impossible to separate different contributions to the recorded signal. This is especially the case for heterogeneous soils under natural forcing, where the determination of soil water content both from ray-path based common offset analysis or the apparent slope in WARR radargrams rarely yield satisfying results (see e.g. [8]).

In the meantime, significant advances have been made when resorting to special circumstances, e.g. in situations where waveguiding occurs (e.g. [9], [10]). Typically involving the presence of frozen layers (e.g. [11], [12]), this type of analysis has recently been expanded for deriving water contents from precipitation induced wave guides [13].

Still, the possibility of a ray-based evaluation of the direct ground wave signal remains intriguing, especially if data recorded in the common-offset profiling mode could be used. Establishing a reliable proxy relation for this kind of ground wave data would be especially beneficial for providing fast and efficient ground truth measurements at the field scale to even larger scale air- and satellite-based remote sensing methods, currently still suffering from substantial uncertainties (e.g. [14]).

In this paper, we explore the stability of the near surface GPR signal along a 0.6 km long measurement line, crossing several vegetated sand dunes at a semi-desert site in Northwestern China. These GPR measurements were aimed at determining the spatio-temporal structures and variations of near-surface soil water contents at scales up to several hundred meters.

II. Site Description

The GPR data were recorded in April 2010 at the onsets of the Gurbantüngüt Desert, approximately 70 km northeast of Urumqi, Xinjiang, P.R. China. This area is situated at the foot of the Bogda mountain range, at only about 400 m above sea-level.

The groundwater table is rather shallow and already reaches the surface at some places. In connection with the strong radiative forcing of a semi-desert environment, this leads to a strongly ascending movement of dissolved salts. At some places, those high salt contents result in large values of electrical conductivity.

The site chosen for this study is characterized by long ranges of sparsely vegetated chains of dunes roughly running along a north-south direction. Dune heights are some 40 m, with interdune spacing between 50 and 100 m. This morphology has distinct implications for the soil water content patterns as will be shown below.

The measurements presented here were taken right after the annual snow melt. This melting snow represents the largest natural water input, with only very little additional precipitation beyond some light rain in spring.

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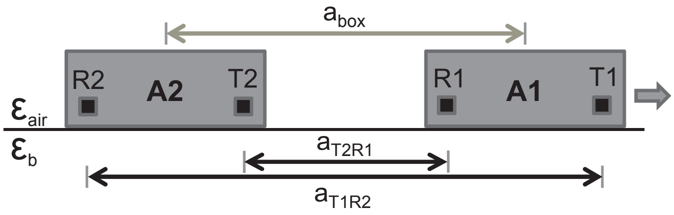


Fig. 1. Schematic view of the antenna setup. The black double-arrows mark the assumed raypath for the two cross-box channels which are used for evaluation (short cross-box channel: a_{T2R1} and long cross-box channel: a_{T1R2}), the grey arrow marked a_{box} denotes the antenna-box separation; direction of movement is to the right.

III. Material and Methods

The GPR measurements were aimed at determining the spatio-temporal structures and variations of near-surface soil water contents at scales up to several hundred meters. The GPR data for this study were acquired along a roughly 550 m long profile, perpendicularly crossing four north-south aligned dune chains.

We employed an IDS multi-channel instrument in a common offset setup (see Fig. 1). This setup consists of two shielded antenna boxes (A1 and A2), each containing one transmitter (T) and one receiver (R). Measurements were taken at nominal center frequencies of 200 and 400 MHz. The internal T-R separation a_{int} in each antenna box for the 400 (200) MHz antennas is 0.14 (0.19) m.

For both center frequencies, the profile was consecutively measured with two different antenna-box separations a_{box} (1 m and 1.5 m), all acquired within a time period of approximately two hours. For each of these four profiles, we evaluate the two cross-box signals (compare Fig. 1):

- T2R1, which is the shorter cross-box channel for every specified antenna-box separation: $a_{\text{T2R1}} = a_{\text{box}} - a_{\text{int}}$
- T1R2, the respective longer cross-box channel: $a_{\text{T1R2}} = a_{\text{box}} + a_{\text{int}}$

This yields two radargrams at each employed antenna-box separation. Thus, we have a total of eight data sets to consider (TABLE I).

The calculation of water contents relies on measuring the travel times along an assumed straight travelpath between the respective transmitters (T) and receivers (R) for each channel, as illustrated in Fig. 1. We employ a semi-automated picking algorithm to follow a distinct feature of the ground wave wavelet throughout the whole radargram. We decided to pick

TABLE I
Overview of the GPR datasets

profile name	f [MHz]	a_{box} [m]	a_{T2R1} [m]	a_{T1R2} [m]
P1	400	1.00	0.86	1.14
P2	400	1.50	1.36	1.64
P3	200	1.00	0.81	1.19
P4	200	1.50	1.31	1.69

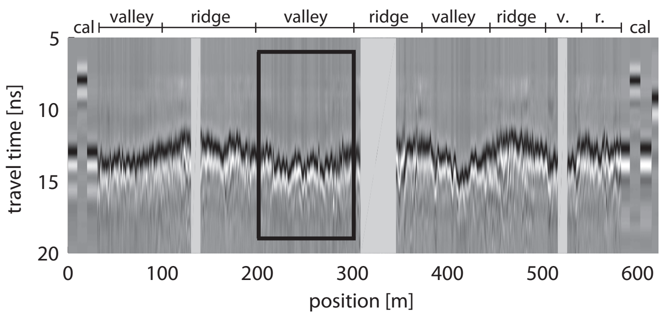


Fig. 2. Exemplary radargram for the complete GPR line under investigation, showing the P1_T1R2 data (400 MHz, $a_{\text{box}} = 1$ m, evaluating T1R2). Profile parts before 20 m and beyond 580 m are used for calibration purposes, profile parts where the ground wave signal is notably influenced by subsurface root systems are masked out. The black box indicates the first inter-dune valley, which is more closely investigated in Fig. 3.

a central feature, here the central minimum of the wavelet to minimize the possible effect of interferences with other signal parts. Time zero correction is carried out by comparing the travel time t_{AW} of the signal measured at antenna separation a in air to theoretical expectations (as has been similarly applied e.g. in [16], [6]):

$$t_{\text{off}} = t_{\text{AW}} - \frac{a}{c}, \tag{1}$$

where c is the speed of light in free space. To reduce the influence of the shielding of the employed antennas, we turned them sideways to truly record the signal through the air. To ensure temporal stability of the signal, we record some traces in air at the start and the end of each profile, this is indicated in Fig. 2.

This then allows calculating the bulk dielectric permittivity ϵ_b from the measured ground wave travel time, the antenna separation and the free space wave velocity at each point of the considered profile:

$$\sqrt{\epsilon_b} = \frac{c \cdot (t_{\text{GW}} - t_{\text{off}})}{a} = 1 + \frac{a}{c} \cdot (t_{\text{GW}} - t_{\text{AW}}). \tag{2}$$

The dielectric permittivities were converted into volumetric soil water content using the CRIM dielectric mixing model (as applied, e.g., by [15]):

$$\theta = \frac{\sqrt{\epsilon_b} - \sqrt{\epsilon_s} - \phi\left(1 - \sqrt{\epsilon_s}\right)}{\sqrt{\epsilon_w} - 1} \quad , \tag{3}$$

where ϵ_s, and ϵ_w are the relative dielectric permittivities of the soil matrix (we here assume $\epsilon_s = 5$) and liquid water, respectively, ϕ is soil porosity (estimated from gravimetric sampling: $\phi = 0.4$).

Along the profile, multiple point measurements were taken by a Tektronix 1502B cable-tester using vertically inserted TDR probes. Results were compared to GPR data. Furthermore, soil profiles were dug at characteristic locations for gravimetric sampling and further ground truth assessment. Soil samples taken for soil texture analysis were classified according to the USDA soil classification. According to this

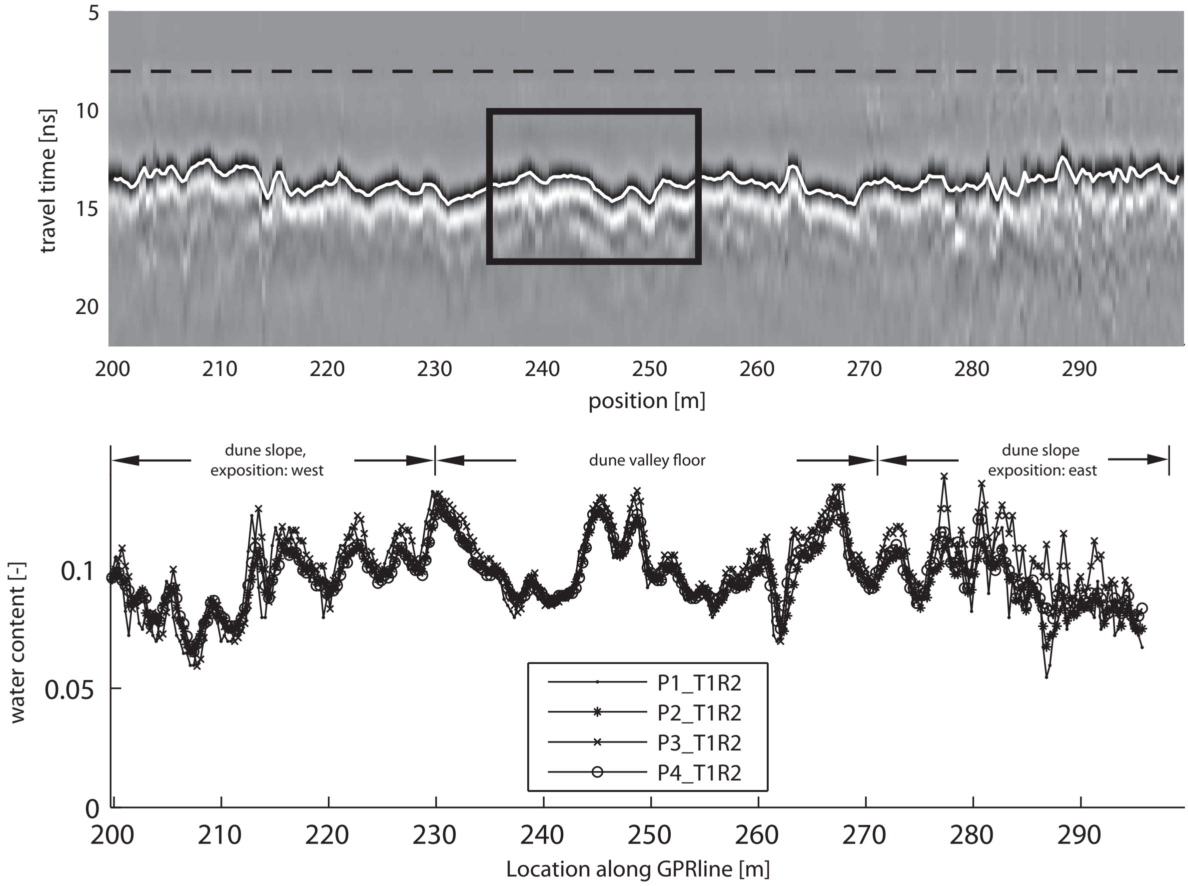


Fig. 3. Exemplary data evaluation for the first dune valley. The upper part shows the corresponding part of the P1_T1R2 radargram out of Fig. 2. The ground wave pick is drawn in white, the employed air wave travel time is indicated by the dashed black line. The black box denotes the stretch of the profile evaluated in more detail in Fig. 4. In the lower part of the figure, the water content evaluation for all T1R2 radargrams are compared. Note the excellent agreement of all data sets along the valley floor (roughly from 230 m to 270 m).

classification, all soil samples acquired from soil profiles along the here considered GPR line belong to the sand or fine sand fraction.

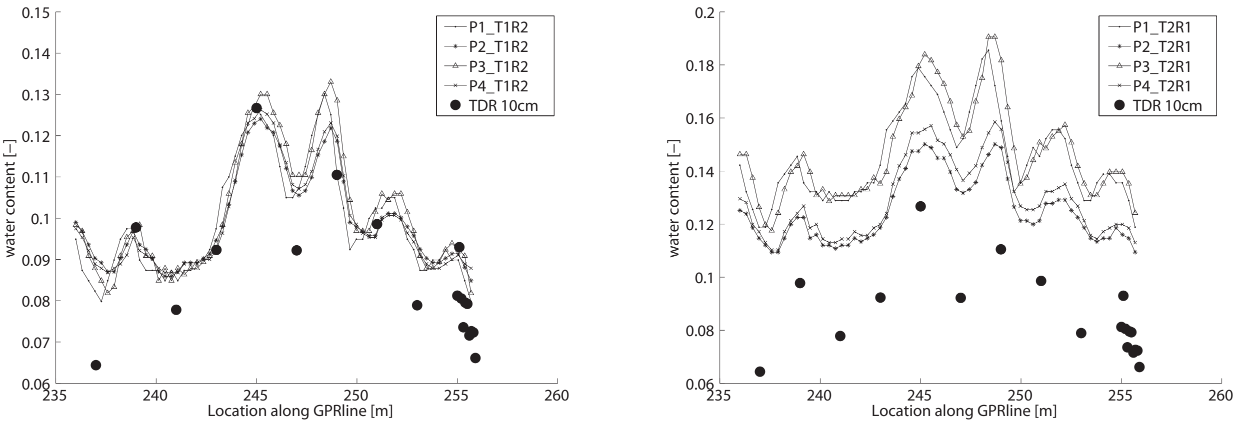
IV. Results and Discussion

One exemplary radargram of the overall GPR line is pictured in Fig. 2. The figure shows the P1_T1R2 data (400 MHz, $a_{\text{box}} = 1$ m, evaluating T1R2), crossing the four dune chains in eastward direction. The profile parts before 30 m and beyond 580 m ("cal") are used for calibration, profile parts where the ground wave signal is notably influenced by subsurface root systems are masked out. Differences between wet parts of the profile, located in between dunes ("valley"), and much drier parts on the upper slopes of the dunes ("ridge") cause obvious changes in recorded ground wave signal travel times. This implies for the situation considered here, that the topography exerts the dominant control on the soil water content distribution at scales of several ten to hundreds of meters.

The large-scale modulations are superimposed on quite significant small-scale soil water content changes. The question arises, if these fluctuations are just due to measurement noise or whether this can be truly associated with smaller scale soil water content differences. Thus we firstly establish the stability of the signal as a basis for all further considerations. To this end, we focus on the part of the profile measured in the dune valley between the first two dune chains, roughly extending between 200 m and 300 m (black box in Fig. 2). We comment that all conclusions drawn from this section remain valid for other dune-valley parts of the profile.

The radargram of the P1_T1R2 profile for this section is shown in the upper part of Fig. 3, where the ground wave pick is drawn in white and the dashed black line indicates the air wave travel time used for evaluation. Water contents derived from this radargram and all available T1R2 (long channel) data of the consecutively acquired three other profiles are shown in the lower part of Fig. 3.

We first note the good reproducibility of the measured data, most notably for the profile parts along the valley floor, where almost every feature of the signal is reproduced in later profiles. Significant deviations do not occur before the



(a) Data derived from the long cross-box channel

(b) Data derived from the short cross-box channel

Fig. 4. Comparison of water contents measured by GPR and TDR along the 20 m stretch indicated in Fig. 3. Employed antenna separations and frequencies for P1…P4 are summarized in TABLE I.

onsets of surrounding dune chains, where an exact retracing of the previously measured profile becomes challenging. Secondly, data evaluation from profiles acquired with different frequencies yield approximately the same results. Meanwhile, measuring at longer antenna separations just averages out more of the small scale variations, as would be expected due to the larger averaging volume.

Furthermore, the GPR ground wave signal is not only very stable, but seems to be an excellent proxy for soil water content. This can be seen when comparing the GPR derived water contents to data acquired with TDR probes of 10 cm rod length (Fig. 4). These TDR data have been measured vertically at several points along a 20 m long stretch of the profile (its position is indicated by the black box in the radargram of Fig. 3). Overall, the data fit quite well. Both TDR and GPR data follow the same trends along the profile; the GPR derived water content values are on average about 0.01 (1% vol.) higher than those derived from TDR. These differences could for instance be explained by the differing averaging volumes of the respective methods. Indeed, measurements from a soil profile excavated close to the 260 m point of the profile indicate a slowly increasing moisture content with depth. With the TDR measuring in the top 10 cm, a somewhat larger averaging depth of GPR would explain the observation. Hence, having just these long channel data sets, one would conclude that under the conditions considered here, reliable values for near-surface water content can be obtained from GPR ground wave data in the fashion described above.

However, the situation becomes somewhat more complicated, with the corresponding T2R1 data, representing the short cross-box channel at each antenna-box separation (Fig. 4b). Here, the same evaluation procedure leads to a very similar shape of the water content changes along the profile, albeit with a distinctive offset in retrieved absolute water contents. Hence, although a proxy relationship holds, this results in absolute water content values that differ both from the previously considered T1R2-data and the TDR measurements. This effect seems to depend notably on the employed antenna separation (higher over-estimation of water contents for shorter antenna separation) and to a much lesser extent also on the employed frequency (slightly higher over-estimation for the 200 MHz data).

We hypothesize that the accuracy of the measured water contents is limited by the current feature-to-feature evaluation of the air- and ground wave wavelets, i.e., by picking the same feature like a maximum or a zero-crossing in both wavelets. This is impeded by:

- the different shapes of the wavelet in air and in the ground, due to the influence of the air-soil interface [17],
- the interference between air- and ground wave for short antenna separations, although they are desirable for high-resolution measurements, and
- the modification of the ground wave signal by the antenna-ground coupling.

The first issue leads to a constant offset between the measured and the true water content. This can be resolved by an appropriate calibration.

The second issue suggests that, depending on the subsurface conditions, we in fact measure a superposition of the ground wave wavelet with some remainder of an air wave wavelet, distorted by the antenna shielding. Neglecting this effect leads to the significant bias for water content determination from the T2R1 data. For the T1R2 data (the longer cross-box channel), this effect appears to be much less an issue, since in this case, the air wave signal is shielded more efficiently. This results both in a delay of the signal arrival time and a decrease in amplitude, reducing its effect on the ground wave. Hence, a more effective physical supression of the direct air wave signal at short antenna separations could resolve this issue. Measurements at larger antenna separations increase the offset between air and ground wave and thus are affected to a lesser extent, albeit at the expense of signal strength and measurement resolution. Having a larger bandwidth, wavelets at higher center frequencies are somewhat less affected as well, since a narrower wavelet reduces a possible overlap.

The third issue also leads to an unpredictable bias which is very hard to remove, however. It may become important at highly heterogeneous sites where the surface water content varies in a wide range. This was not the case in the current study such that this effect may safely be ignored.

V. Conclusions

We have shown that the GPR ground wave signal can be reliably reproduced in successive measurements, across extended periods of space and time. Along a 550 m long profile in a semi-desert environment, almost every water content peak could be reproduced for profile parts measured between dune chains, even when employing different frequencies (200 / 400 MHz). The comparison of T1R2 data with TDR measurements shows that this signal displays a strong relationship to near-surface soil water content. However, the evaluation of the T2R1 data seems to substantially over-estimate water content values. We attribute this to limitations of the current direct feature-to-feature evaluation of the air- and ground wave wavelets.In general, directly using the recorded signal in air as a reference does not allow for enough precision for reliably determining quantitative soil water content values from common-offset ground wave data without additional auxiliary information.

A more efficient supression of the direct air wavelet would solve a part of this issue. Otherwise, a more sophisticated way of data evaluation is needed for the evaluation of ground wave signals measured at short antenna separations.

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