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1 Introduction

This practical course is embedded in the large scientific field of soil hydrology. It focuses primarily on the water distribution and the water movement in soils. In the experiments of this course, the main aspect is the measurement of the soil water content in the laboratory as well as in the field. Here, the water content will be measured with two geophysical methods: time domain reflectometry (TDR) and ground penetrating radar (GPR).

Motivation

The surface water content is of high significance for life on earth. Obviously it determines the plant cover and therefore life in a fundamental perspective. But it has also a huge impact on the climate. For instance, the dramatic day and night time temperature changes in deserts compared to the temperate zone can be traced back to the lack of water. Here, one factor is the evaporation of the existing water at the soil surface in the daytime. This leads to a cooling of the soil surface. Furthermore, the water in the soil stores the thermal energy at daytime. In the nighttime, this energy is emitted again.

Measuring the Volumetric Water Content

There is a huge variety of methods, which aim to measure the water content of the soil. These methods can be distinguished in direct or indirect, in invasive or non-invasive techniques as well as concerning to the scale of their application. Here, indirect measurements are methods, where the water content is obtained via physical proxy quantities such as dielectric material properties. In the following only a few examples will be given to measure the soil water content.

The most prominent direct and invasive technique is the gravimetric method. Here, a previously extracted moist soil sample with a known volume is weighted, dried and weighted again. From this, one can obtain the gravimetric as well as the volumetric water content at a single point. Disadvantageously, this method is very time consuming, when studying the distribution of the water content at the field scale.

An example for an indirect and almost non-invasive techniques is the neutron probe, which can be installed in a borehole. Here, neutrons are emitted and transmitted through the soil sample of interest. The scattering of these neutrons depends on the amount of water
in the soil. Unfortunately, this technique is again only applicable on a local scale and it is not completely without healthy risks for the operator.

Some measurement techniques of the soil water content are based on the dielectric method. Here, the dielectric permittivity of the soil is used as a proxy for the volumetric water content, because the relative permittivity of water ($\varepsilon_{\text{water}} \approx 80$) is significantly higher than of the soil matrix ($\varepsilon_{\text{matrix}} \approx 4 - 5$) and of the air ($\varepsilon_{\text{air}} = 1$) within the soil pore space. Examples for this class of techniques are the time domain reflectometry (TDR) and the ground penetrating radar (GPR), which will be applied in this practical course. For both applications the travel time of either guided or free electromagnetic waves is measured, which is closely related to the relative permittivity of the medium via the electromagnetic wave velocity. Here, TDR can be recognized as a method for local measurements, where GPR is applied on the regional scale for water content measurements for a few tenth to hundreds of meter survey length.

**Comments on the Preparation**

For the preparation of this practical course, this manual should be enough. Therefore it is at least required to read this manual carefully before the beginning of the practical course.


**Guiding Questions**

1. On which physical and environmental processes does the water content have a major impact?

2. What is the measurement principle of time domain reflectometry?

3. What is the measurement principle of ground penetrating radar?

4. What are the advantages and disadvantages of both methods?

**Questions for some own Thoughts**

5. Which physical and environmental parameters can lead to water content changes in the soil?
6. How can water be distributed vertically in the soil and which physical processes determine this distribution?
2 Theory

For this practical course it is necessary to understand the main ideas and principles of electromagnetic wave theory in inhomogeneous or piecewise homogeneous media. For this purpose, a short introduction on the fundamental equations as well as on the electromagnetic wave propagation, attenuation and reflection processes will be given. Finally, the main aspects concerning the dielectric material properties in soils are highlighted.

2.1 Electromagnetic Wave Propagation in Matter

2.1.1 Maxwell’s Equations and Preliminary Assumptions

The relevant Maxwell’s equations to study electromagnetic wave propagation are

\[ \nabla \times \mathbf{H}(\mathbf{r}, t) = \mathbf{J}_{\text{ext}}(\mathbf{r}, t) + \frac{\partial}{\partial t} \mathbf{D}(\mathbf{r}, t) \quad (2.1) \]
\[ \nabla \times \mathbf{E}(\mathbf{r}, t) = -\mu_0 \frac{\partial}{\partial t} \mathbf{H}(\mathbf{r}, t) \quad . \quad (2.2) \]

[\( \mathbf{E} \) - electrical field, \( \mathbf{D} \) - displacement current, \( \mathbf{H} \) - magnetic field]

[\( \mathbf{J}_{\text{ext}} \) - external current density, \( \mu_0 \) - vacuum permeability \( (4\pi \times 10^{-7} \text{N/A}^2) \) ]

Here, the equations are given for non-magnetic matter, because the most materials related to the experiments in this practical course are not magnetizable. Therefore, the relative magnetic permeability is set to 1. This is only violated, when soils with a non-negligible iron content are studied.

Furthermore, in Eq. (2.1) an external current density is mentioned. It is the source of the electromagnetic waves and therefore represents the antenna in the system.

2.1.2 The Electrical Conductivity

The electric conductivity results, when an incoming electric field leads to a movement of unbounded charge carriers. For its description, one can start with the equation of motion
2 Theory

according to Drude (1900)

\[
\frac{\partial^2 s(r, t)}{\partial t^2} + g \frac{\partial s(r, t)}{\partial t} = \frac{q}{m} E(r, t) \quad .
\]

[ \( s \) - elongation of particles from an initial position, \( g \) - damping term due to friction / collisions ]

[ \( m \) - mass of the particles, \( q \) - charge of the particles ]

The movement of all particles with a particle density \( n \) leads to a resulting current density \( J \), which is given as

\[
J(r, t) = -n q \frac{\partial s(r, t)}{\partial t} \quad .
\]

Substituting this into Eq. (2.3), this results

\[
\frac{\partial}{\partial t} J(r, t) + g J(r, t) = \frac{q^2 n}{m} E(r, t) \quad .
\]

After a Fourier-transformation, rearranging the equation and employing Ohms Law \( J(r, \omega) = \sigma(\omega) E(r, \omega) \), we obtain

\[
\sigma(\omega) = \frac{q^2 n}{(g - i \omega) m} \quad .
\]

[ \( \sigma \) - electrical conductivity. ]

Important: The electric conductivity is an effect of unbounded charge carriers and is in general a complex function of frequency. As can be seen in equations 2.17 and 2.18 attenuation of electromagnetic waves partly goes back to the real part of \( \sigma(\omega) \) which itself depends on the damping factor \( g \) (You can see this by reformulating equation 2.6). Hence one can say that the damping of the movement of free charge carriers partly causes the attenuation; a fact that is quite intuitive. When using microwaves - as we do here - the damping term \( g \) is found to be dominating in equation 2.6. Then, the electric conductivity function reduces to the direct current electric conductivity \( \sigma_{dc} = \frac{q^2 n}{g m} \).

2.1.3 The Dielectric Permittivity

The influence of dielectric material properties is introduced in the displacement current \( D \). Here, the idea is that an incoming oscillating electric field can lead to a polarization in the medium. This can be expressed as

\[
D(r, t) = \varepsilon_0 E(r, t) + P(r, t) \quad .
\]

[ \( P \) - polarization, \( \varepsilon_0 \) - vacuum permittivity (\( 8.854\ldots \times 10^{-12} \text{A}^2\text{s}^4/\text{kg m}^3 \) ) ]

This polarization results from displaced charges due to the electric fields\(^1\). Furthermore, the response due to the polarization induced by an incoming electric field is assumed to

\(^1\)A polarization can also be induced by the magnetic field. In the scope of this work, this will be neglected.
be linear, which is only violated in the research field of high energy laser physics. This response of the polarization need not to be instantaneous and it can have an aftereffect, which leads to a general description given as

\[ P(r, t) = \int_{-\infty}^{t} R(r, t - t') E(r, t') \, dt' \]  

(2.8)

which is a convolution of a response function \( R \) and the electric field. This response function describes how the medium reacts, when a single and very sharp electric field excitation (delta-excitation) occurs.

This expression leads to a simple product in the frequency domain, which yields

\[ P(r, \omega) = \chi(r, \omega) E(r, \omega) \]  

(2.9)

where \( \chi \) represents the Fourier transformation of the response function \( R \). Then, Eq. (2.7) leads in the frequency domain with Eq. (2.9) to

\[ D(r, \omega) = \varepsilon_0 \left( 1 + \chi(r, \omega) \right) E(r, \omega) = \varepsilon_0 \varepsilon^*(r, \omega) E(r, \omega) \]  

(2.10)

Here, \( \varepsilon^*(r, \omega) := 1 + \chi(r, \omega) \) is defined as the relative dielectric permittivity\(^2\) of the medium.

**Important:** The relative dielectric permittivity is a quantity of the energy storage of the medium, due to a polarization of the medium. In the case that the response of the medium concerning an incoming electric field is instantaneously and without any aftereffect, than the relative permittivity is a constant. But in general it must be considered as a complex function

\[ \varepsilon^*(\omega) := \varepsilon''(\omega) + i \varepsilon''(\omega) \]  

(2.11)

depending on the frequency of the incoming electrical field. So, if each frequency component of an incoming electric signal leads to a different response of the medium, the outgoing signal is deformed. This is called dispersion.

One possible model to do derive a functional expression for \( \varepsilon^*(\omega) \) is given by the Drude model [Jackson (2006), p. 358 ff.]. This model assumes that the polarization of the medium is caused by atomic electrons which are located in a harmonic force field leading to an additional term \( \omega_0^2 s(r, t) \) on the left hand of equation 2.3. This means that these electrons are assumed to be bound (by the harmonic force), which is the decisive difference to the derivation of the electrical conductivity in section 2.1.2. Exactly the bounding force leads to the appearance of resonance absorption: In certain frequency ranges (absorption bands) around the resonance frequency \( \omega_0 \) the entity \( \varepsilon''(\omega) \) cannot be neglected and causes the attenuation of electromagnetic waves (equation 2.17).

Howsoever, the derivation of the functional expression for \( \varepsilon^*(\omega) \) is of minor importance for this practical course. Hence, you are referred to the literature sources for a deeper inside.

\(^2\)Normally, the notation \( \varepsilon_r \) can be found in the literature for the relative dielectric permittivity. Because, we always refer to this value in the scope of this manual, we neglect the index \( r \).
2 Theory

Note: Electrical conductivity and the dielectric permittivity can be subsumed under a general relative permittivity via

$$\varepsilon(\omega) := \frac{\sigma(\omega)}{i \omega \varepsilon_0} + \varepsilon^*(\omega).$$  

(2.12)

Obviously, this entity is in general a complex number with $\varepsilon(\omega) = \varepsilon'(\omega) + i \varepsilon''(\omega)$. (For simplicity reason, we keep the previously mentioned notation of the relative permittivity $\varepsilon$.)

2.1.4 Propagation of Electromagnetic Waves

An adequate approach solving Eq. (2.1) and (2.2) is the plane wave approach\(^3\). A single plane wave is mathematically described as

$$E(r, t) = E_0 e^{i(\omega t - k \cdot r)}.$$  

(2.13)

[ $E_0$ - amplitude factor, $k$ - propagation vector ]

Here, the propagation vector gives mainly the propagation direction. With respect to Maxwell’s equations, the dispersion relation

$$|k|^2 = \omega^2 \mu_0 \varepsilon_0 \varepsilon(\omega) = \frac{\omega^2}{c_0^2} \varepsilon(\omega)$$  

(2.14)

[ $c_0=(\varepsilon_0 \mu_0)^{-1/2}$ - speed of light in vacuum ($c_0 \approx 0.3$ m/ns) ]

must be fulfilled. From this it is obvious that the length of the propagation vector depends on the frequency and cannot be chosen arbitrarily.

Propagation Velocity and Attenuation of Plane Waves

Attenuation of a single plane wave always appears if $\varepsilon''(\omega) \neq 0$. To understand this fact, we assume a plane wave propagating in the $x$-direction. Then, the phase of Eq. (2.13) can be rewritten as

$$i(\omega t - k_x x) = i(\omega t - (\alpha - i \beta) x) = -\beta x + i(\omega t - \alpha x),$$  

(2.15)

where $\alpha$ and $\beta$ are defined as the real and imaginary part of the $x$-component of the propagation vector. Inserting this reformulation into Eq. (2.13), we can see that $\alpha$ is

\(^3\)Mathematically this means that two plane waves propagating in opposite directions (linearly independent!) are a fundamental solution of the Maxwell equations for a given frequency. And because of the linearity of Maxwell’s equations any linear combination of plane waves with different frequencies obviously is a solution as well; hence a big function space is covered by this, including wavelets (section 2.3.2) etc. . Thinking in the opposite direction, it also means that any observed electromagnetic field (which by definition is a solution to Maxwell’s equations) can be represented by a linear combination of plane waves. A fact that is expressed by the often applied Fourier Transform or frequency decomposition. This all enhances the importance of plane waves and explains why it is typically sufficient to stay limited to plane waves in solving electrodynamic problems.
responsible for the propagation and $\beta$ for the attenuation. The expressions for $\alpha$ and $\beta$ as functions of $\varepsilon'$, $\varepsilon''$ and the frequency can be derived via

$$\alpha - i \beta = \frac{\omega}{c_0} \sqrt{\varepsilon' - i \varepsilon''}$$  \hspace{1cm} (2.16)

$$\Rightarrow \alpha = \frac{\omega}{c_0} \sqrt{\frac{\varepsilon' + \sqrt{\varepsilon'^2 + \varepsilon''^2}}{2}} \quad \text{and} \quad \beta = \frac{\omega}{c_0} \sqrt{\frac{-\varepsilon' + \sqrt{\varepsilon'^2 + \varepsilon''^2}}{2}}. \hspace{1cm} (2.17)$$

Now, focusing on the remaining phase term, we can find that the phase is always constant for $v = \frac{\Delta x}{\Delta t} = \frac{\omega}{a}$ where $v$ is the propagation velocity.

**Important:** The velocity and the attenuation of a plane wave are functions of both real and imaginary part of the relative permittivity. Generally, they depend on frequency, meaning that each frequency component of an initial electromagnetic wave front is affected differently. This effect is called dispersion of a wave front.

Now assuming that the relative permittivity has only a small imaginary part, which is only influenced by the electric conductivity, then the plane wave propagation in $x$-direction in the medium can be described as

$$E(x, t) = E_0 \exp \left\{ -\frac{\sigma_{dc} x}{2 c_0 \varepsilon_0 \sqrt{\varepsilon'}} \right\} \exp \left\{ i \omega \left( t - \frac{\sqrt{\varepsilon'}}{c_0} x \right) \right\}. \hspace{1cm} (2.18)$$

Therefore, under these assumptions the attenuation is not a function of frequency. Furthermore, the propagation velocity reduces to

$$v = c_0/\sqrt{\varepsilon'}. \hspace{1cm} (2.19)$$

**Note:** The terms *attenuation* and *absorption* are not consistently used in literature. Sometimes both expressions are used equivalently what increases confusion and is obviously redundant. Thus we want to distinguish between the two processes here, according to the following definition: Absorption is only related to the processes included in $\varepsilon''(\omega)$: resonance absorption and the damping of free charge carrier movement. Attenuation says something about the electromagnetic wave amplitude: Inserting the equations 2.17 in 2.15 and further in 2.13, we directly see that the plane wave is attenuated by the factor $\exp\{-\beta x\}$ ($\beta$ is sometimes also called attenuation coefficient). Hence, attenuation includes all factors in $\beta$ and with that imaginary and real parts of $\varepsilon$. Therefore absorption is included as well as scattering and other effects. However, it is interesting to notice that $\varepsilon'' \neq 0$ ($\rightarrow$ absorption) is still a necessary condition for $\beta \neq 0$ ($\rightarrow$ attenuation). This might be one reason for the given confusion on the two terms.

### 2.2 Guided Waves / Transmission Line Theory

Eqn. (2.1) and (2.2) are the general expressions of Maxwell’s theory, they can be easily applied to study the propagation of freely propagating waves. If we focus on guided waves in conductors, then the geometry plays a significant role in the wave propagation.
The theory of the propagation of guided waves in electromagnetism is subsumed in the transmission line theory. Here, the relevant observable quantities are the voltage \( V \) and the current \( I \). The wave equation in frequency domain for both quantities propagating only in one dimension (\( x \)-direction) are

\[
\begin{align*}
\partial^2_x V(x) + \omega^2 LC V(x) &= 0 \quad (2.20) \\
\partial^2_x I(x) + \omega^2 LC I(x) &= 0 \quad (2.21)
\end{align*}
\]
[\( L \) - inductance, \( C \) - conductance]

Using a similar approach as Eq. (2.13) for the voltage or the current, one can obtain a propagation velocity

\[
v = \frac{1}{\sqrt{LC}} = F \frac{1}{\sqrt{\mu_0 \varepsilon_0 \varepsilon}} = F \frac{c_0}{\sqrt{\varepsilon'}} . \quad (2.22)
\]

Here, a form-factor \( F \) is introduced in order to account for the fact, that the velocity is influenced by the geometry of the system. (In this practical course the TDR probes are designed in a way, that \( F \) can be assumed as 1.)

### 2.3 Measuring Material Properties with Electromagnetic Waves

When applying electromagnetic waves to measure material properties, one could basically use two different techniques: (i) transmission or (ii) reflection. For both methods, one can either evaluate the travel time or the electromagnetic wave amplitude to obtain information about the material, in which the wave was propagating.

Because in this practical course, we will focus on reflection measurements, a short overview of the concepts used for this measurement type will be given.

#### 2.3.1 The Reflection Coefficient

For freely propagating waves a reflection always occurs, when the material properties are changing. Assuming the magnetic permeability to be constant and a perpendicular incidence, the reflection coefficient is given as

\[
R = \frac{\sqrt{\varepsilon_1} - \sqrt{\varepsilon_2}}{\sqrt{\varepsilon_1} + \sqrt{\varepsilon_2}} . \quad (2.23)
\]
[\( \varepsilon_1 \) - relative permittivity of the upper layer, \( \varepsilon_2 \) - relative permittivity of the lower layer]

This is a special formulation of Fresnel’s equation for the reflection of electromagnetic waves. The Reflection coefficient is the amplitude ratio of the incident to the reflected wave. Thus, its sign indicates a possible phase shift: if \( R < 0 \) a phase factor \( e^{i\pi} \) is given. In case of a wavelet (next section), this means that the wavelet is flipped such that positive amplitudes get negative and vice versa.
Note: This equation is not generally valid for guided waves. Here, a change in the geometry can also lead to a reflection, although the material properties remain constant.

2.3.2 Wavelet Concept

In the field of GPR and TDR applications, it is assumed that an electromagnetic pulse with a finite duration in time and a specific shape is emitted. This pulse propagates in the adjacent medium and it is either directly transmitted to the receiver or it reaches the receiver after one or several reflections. The sum of all incoming pulses is the measured signal.

This pulse can be called wavelet and therefore, the measured signal can be considered as a superposition of wavelets, where each wavelet travels along a different propagation path.

In a lot of cases, the measured signal cannot be simply decomposed. For TDR applications this is mainly due to the dispersion of the initial pulse. For GPR applications this results from the superposition of different wavelets. Hence, in most applications either of TDR or GPR, one is trying to identify significant wavelet features. Assuming them to stay almost undisturbed, one can describe the propagation of these features with the ray approach.

2.4 The Relative Dielectric Permittivity of Soils

Soils can be considered as a three phase medium consisting of the soil matrix, air and water. Therefore, one has to study the permittivity of each constituent and then of the mixture. Since the permittivity is determined by measuring the wave propagation velocity, only the real part $\varepsilon'$ can be measured (equation 2.19) and is considered below.

Because the relative permittivity of air ($\varepsilon'_{\text{air}} \approx 1$) and the soil matrix ($\varepsilon'_{\text{matrix}} \approx 4 - 5$) can be considered as constant values in the frequency range of TDR and GPR, we will focus on the relative permittivity of water and of the mixture.

2.4.1 The Relative Permittivity of Water

Each water molecule can be considered as a dipole, which can be orientated according to an incoming electromagnetic field. This orientation of the molecules depends on the frequency of the incoming field. Hence three cases have to be distinguished.

(I.) If the frequency is too high, the molecules cannot follow and thus, they cannot store electromagnetic energy. This results in a smaller value of the relative permittivity of water.
(II.) If the frequency is slower than the time for the orientation of each molecule, then the polarization of the water can reach its maximum, which results in the highest number of the relative permittivity value.

(III.) For the frequency between these sketched limits, the molecules can follow partially the alternating electromagnetic fields. Therefore, electromagnetic energy is needed to orientate the molecules. This energy is either re-emitted or transformed into thermal energy. This phenomenon is called relaxation process, because the reemission is not instantaneously. Furthermore, it is coupled with absorption of the electromagnetic waves. The frequency at which the most energy is absorbed is called relaxation frequency.

In addition, the capability for the polarization for the water molecules as well as the relaxation process and the absorption of electromagnetic energy is a function of temperature. That is because the Brownian motion, which depends on the temperature, counteracts the orientation of the motions.

**Note:** For frequencies below 1 GHz, the dielectric permittivity of water can be assumed to be frequency independent and the imaginary part can be neglected [Gerhards (2008), p. 17]. Including temperature the \( \varepsilon' \) can be described as a function of temperature according to Kaatze (1989) as

\[
\log_{10} \varepsilon_{\text{water}}' = 1.94404 - 1.991 \cdot 10^{-3} \text{K}^{-1} \cdot (T - 273.15 \text{K}) .
\]  

\[
(2.24)
\]

\[ T \text{ - temperature in K (Kelvin) } \]

### 2.4.2 The Composite Relative Permittivity

The calculation of a composite permittivity is generally a non-trivial issue. If at least one constituent has a single relaxation, then the interaction of all constituents can change this relaxation or lead to a multi-relaxation phenomenon, due to different molecule interactions depending on the distance to surfaces.

If we assume that none of the constituents has a relaxation, a simple mixing formula can be applied, which is called complex refractive index model (CRIM, Roth *et al.* (1990)). Here, the composite dielectric permittivity \( \varepsilon'_c \) is given as

\[
\sqrt{\varepsilon'_c} = \theta \sqrt{\varepsilon'_{\text{water}}} + (\phi - \theta) \sqrt{\varepsilon'_{\text{air}}} + (1 - \phi) \sqrt{\varepsilon'_{\text{matrix}}}.
\]

\[
(2.25)
\]

[ \theta \text{ - volumetric water content, } \phi \text{ - porosity } ]

From this, one can deduce the formula to determine the volumetric water content via

\[
\theta = \frac{\sqrt{\varepsilon'_c} - \sqrt{\varepsilon'_{\text{matrix}}} - \phi (\sqrt{\varepsilon'_{\text{air}}} - \sqrt{\varepsilon'_{\text{matrix}}})}{\sqrt{\varepsilon'_{\text{water}}} - \sqrt{\varepsilon'_{\text{air}}}} .
\]

\[
(2.26)
\]

Here, the composite relative permittivity can be considered as directly measured. The porosity \( \phi \), the relative permittivity of the soil matrix as well as the temperature, which leads to the permittivity of water, must be either assumed or measured additionally.
3 Time Domain Reflectometry

In soil science, time domain reflectometry (TDR) is a state-of-the-art method to measure volumetric water content and electrical conductivity of soils. The measurement principle is based on the analysis of the propagation velocity of guided electromagnetic waves along a TDR probe through the ground. It allows to determine the dielectric properties of the medium which are closely related to water content and electrical conductivity (see chapter 2). For interested students, a comprehensive review of the TDR measurement technique is given by Robinson et al. (2003).

3.1 Measurement Principle

A schematic description of a TDR measurement system is shown in Fig. 3.1. It consists of a TDR device which is composed of a signal generator and a sampling unit, and a TDR probe that is connected to the TDR device via a coaxial cable. The system applied in this practical course is controlled by a computer.

The measurement principle is based on the measurement of the propagation velocity of a step voltage pulse along a TDR probe through the ground. The probe is installed such, that the metal rods are completely surrounded by the soil material. In this experiment we apply 3-rod TDR probes where the probe rods are arranged in a horizontal plane with a constant separation between the rods. In principle, the probe rods can be regarded as elongation of the coaxial cable where the middle rod is the inner conductor and the outer rods represent the outer conductor of the cable. The TDR device generates short electromagnetic pulses (frequency range: 20 kHz to 1.5 GHz) which propagate along the coaxial cable and further along the rods of the TDR probe. At positions where erratic changes in relative permittivity occur, part of the electromagnetic energy is reflected. This is why TDR was initially developed for detecting failures along transmission line cables - TDR devices are also known as “cable testers”. The application in soil science is a modification of this technique. At the head of the TDR probe, part of the electromagnetic energy is reflected due to the impedance jump between the cable and probe head material. The remaining fraction of the signal propagates through the soil along the metal rods which serve as a wave guide. At positions where the dielectric properties of the soil change erratically, the signal is again partially reflected. In soils with low electrical conductivity the remaining part of the electromagnetic energy is finally reflected at the end of the probe rods.

The temporal development of the voltage of the reflected TDR signal is recorded by the
3 Time Domain Reflectometry

Figure 3.1: Measurement principle of a TDR probe and example signal

signal detector of the TDR device. Figure 3.1 shows a characteristic voltage-time diagram as obtained in a TDR measurement. From the signal response we can deduce the electrical properties of the material through which the electromagnetic pulse propagates.

3.2 Determination of the Relative Dielectric Permittivity from the TDR Signal

For the determination of the travel time of the electromagnetic signal along the TDR rods through the soil we use the two significant reflections which occur in the head and at the end of the rods of the TDR probe. From these two characteristic points we can deduce the two-way travel time $t_{rod}$ of the electromagnetic signal through the soil: forth to the end of the probe and back to the probe head. With that one obtains the composite relative permittivity of the material which surrounds the probe rods

$$\varepsilon'_c = \left( \frac{c t_{rod}}{2L} \right)^2,$$

(3.1)

where $L$ is the length of the TDR probe rods. The volumetric soil water content is determined from the measured relative permittivity using the CRIM formula (2.26).

The reflection from the probe head is independent of the material between the probe rods and hence occurs always at the same travel time and serves as a reference in the travel
3.3 Measurement Volume

Figure 3.2: Travel time determination from the TDR signal

time calculation. The travel time of the reflection from the rod ends depends on the propagation velocity of the electromagnetic wave through the soil. The difference of these two reflection points determines the travel time of the electromagnetic signal forth and back through the soil.

The travel time composes of the travel time through the probe head and along the probe rods:

\[ t_{\text{probe}} = t_{\text{head}} + t_{\text{rods}}. \]  \hspace{1cm} (3.2)

For an accurate determination of the soil’s relative permittivity the TDR probes first have to be calibrated in media with known propagation velocities. In our case the calibration is done by conducting TDR measurements in water and air and correcting for the travel time in the probe head.

Determination of the travel time of the electromagnetic signal is done by using the derivative of the TDR signal and taking the largest values of the derivative occurring at the impedance jump in the probe head and at the end of the rod as reference points (see Figure 3.2).

3.3 Measurement Volume

The measurement volume of a TDR probe is the volume of soil which has an influence on the measured TDR signal.

The sensitivity of the TDR probe decreases exponentially perpendicular to the rod axes. The volume fractions shown in Figure 3.3 are determined by the probe geometry and are independent of the permittivity of the surrounding material. The measurement volume is primarily determined by the diameter and the distance between the probe rods: an
3.4 Electrical Conductivity

A comprehensive description for measuring electrical conductivity of soils with TDR is given by Heimovaara et al. (1995). The direct current electric conductivity $\sigma_{dc}$ of the soil can be determined from the amplitude of the reflected TDR signal:

$$\sigma_{dc} = \frac{K}{Z} \frac{1 - R_\infty}{1 + R_\infty}.$$ (3.3)

where $K$ is a constant which is determined by the probe geometry, $Z$ is the impedance of the cable (50 $\Omega$), and $R_\infty$ is the reflection coefficient at very long travel times where no further reflections of the signal occur. At this point the reflection coefficient can be determined by

$$R_\infty = \frac{V_\infty - V_0}{V_0}.$$ (3.4)

where $V_\infty$ and $V_0$ are the signal amplitudes as shown in Figure 3.4.

The probe geometry constant $K$ can be determined by measuring signals in solutions with known electrical conductivity $\sigma_{dc,T}$ (at $T$ °C). Alternatively, $K$ can be determined by

$$K = \left(\frac{\varepsilon_0 \varepsilon'}{L}\right) Z_0.$$ (3.5)

where $\varepsilon_0$ is the electrical field constant, $\varepsilon'$ is the relative permittivity in free space, $L$ is the probe rod length [m] and $Z_0$ is the probe capacity. $Z_0$ can be determined via a reference measurement in non-conductive material, as e.g. de-ionized water using

$$Z_0 = Z \varepsilon'_{ref} \frac{1 + R_0}{1 - R_0}.$$ (3.6)

where $\varepsilon'_{ref}$ is the relative permittivity of the non-conductive medium.
3.5 Concluding Remarks

TDR probes can be installed vertically and horizontally in the soil. This way, one can investigate the complete profile down to a depth of a few meters. As discussed in section 3.3 the effective measurement volume of a TDR probe is relatively small. Hence, water contents determined from this method only represent local point measurements. For a spatial analysis of soil water content at the field scale a huge number of measurements is required. Furthermore, one has to apply adequate interpolation techniques in order to obtain meaningful spatial information about water content distribution. Nevertheless, TDR is still a state-of-the-art technique in classical soil physics.

In order to obtain a good TDR measurement it is necessary to establish a good contact between the soil and the probe rods and to avoid air gaps during installation.

In this practical course we exclusively measure average soil moisture content along the probe rods even if the water content may be changing. Currently inverse techniques are being developed in soil physics which allow to model the TDR signal and estimate spatial changes in soil moisture content along the TDR probe. However, these techniques are computationally intensive and still in a development state and cannot be applied in the framework of this practical course.

Figure 3.4: TDR signals for determination of electrical conductivity. Note, that the TDR100 device used in the practical course directly translates measured voltages into reflection coefficients.
3 Time Domain Reflectometry
4 Ground Penetrating Radar

Ground penetrating radar (GPR, RADAR = RAdio Detection And Ranging) is a state-of-the-art geophysical measurement technique which can be applied to explore near-surface underground structures. The measurement principle is based on the transmittance of high-frequency electromagnetic pulses into the ground. The travel time of the emitted pulses is subsequently recorded by a receiving antenna.

4.1 Measurement Principle

Standard ground penetrating radar systems consist of a transmitting and a receiving antenna. High-frequency (range: 50 MHz to 1 GHz) electromagnetic pulses are emitted into the ground by the transmitting antenna. The radar wavelet propagates through the soil while the velocity of the wavelet depends on the dielectric properties of the ground. At interfaces, e.g., boundaries of different soil layers or distinct objects, where the dielectric properties of the different media change erratically, the electromagnetic wave is partially reflected. The travel time and amplitude of the wavelet is recorded by the receiving antenna.

In contrast to the TDR technique which has been discussed in the previous chapter, GPR operates with “free” waves. The travel time of the wavelet which is recorded by the receiving antenna depends on the path along which the wavelet propagates and the dielectric properties of the materials. Figure 4.2 shows travel path of various wave types through the soil which may occur in the presence of two layers with different relative permittivities.

The first wavelet which is detected by the receiving antennas the so-called air wave which propagates through the air between both antennas with the vacuum speed of light. The second wavelet which reaches the receiver is the so-called ground wave. It propagates also directly between the transmitter and the receiver along the air-soil interface and can be applied to infer the near-surface soil moisture content. Air- and ground wave are also known as “direct waves” which always occur, independent of soil structure.

In layered soils we can detect further, reflected and refracted wavelets. Reflections occur at interfaces between soil layers with different dielectric properties. If \( \varepsilon_1' > \varepsilon_2' \), a further type of wave, the so-called refracted wave originate which propagates parallel to the boundary of the second layer. In addition, combinations of these primary wave types shown in Figure 4.2 may occur in the radargram which are not discussed here.
Figure 4.1: Ground penetrating radar measurement principle

Figure 4.2: Travel paths of different GPR wave types in a two-layer soil with different relative permittivities.

The signals of the various emitted wavelets reach the receiving antenna at different times. Plotting the recorded amplitudes as a function of time results in a so-called “trace”. Figure 4.3 shows a trace which consists of air wave, ground wave and reflected wave.

In a standard GPR measurement, the antennas are pulled along the survey track while traces are triggered at a fixed interval by a measurement wheel which is connected to the back of the antenna. This results in a series of traces which are finally displayed by the measurement software as a function of position and time in a so-called radargram.
4.1 Measurement Principle

Figure 4.3: GPR trace. Note, that a wavelet always consists of a number of “wiggles” which are displayed in the radargram as a series of lines (e.g. red-blue-red).

Figure 4.4: (a) Origin of a radargram. Amplitudes which exceed a pre-defined positive or negative threshold are displayed in color. In this example negative amplitudes are shown in blue while positive amplitudes are displayed in red; modified after (Reynolds, 1997) (b) Example radargram.
4.2 Measurement System

A GPR measurement system consists of a transmitter and a receiver antenna and a control unit (see Figure 5.3). In the system applied in this practical course both antennas are placed in one box. The dimensions of these box are given in Figure 4.5.

The main part of the GPR system is the control unit which generates the GPR signal and also receives the signals after their passage through the ground. The complete system is computer controlled. The measurement wheel at the back of the antenna box measures the distance along the survey track and triggers the emittance of the electromagnetic pulses.

4.3 Measurement Setups

4.3.1 Common Offset (CO)

Common Offset is the simplest and most widespread GPR measurement technique. In this setup transmitter and receiver antennas are moved along the survey track while the distance between both antennas is kept constant throughout the whole survey. Electromagnetic pulses are emitted at equidistant intervals which are controlled by the survey wheel. With this measurement technique one can efficiently and fast obtain information about the near-surface underground structure.

From the measured travel time \( t \) of the reflected electromagnetic signal one can determine...
the depth $d$ of a horizontal reflector Figure 4.6

$$s = 2 \cdot \sqrt{d^2 + \left(\frac{a}{2}\right)^2} = \sqrt{4d^2 + a^2}, \quad (4.1)$$

where $a$ is the distance between transmitting and receiving antenna. Assuming a homogeneous medium the travel time is determined by

$$t = \frac{s}{v} = \frac{\sqrt{4d^2 + a^2}}{c \sqrt{\varepsilon}}. \quad (4.2)$$

If the depth of the reflector is known, the relative permittivity can be determined which finally allows the calculation of the average volumetric water content of this layer via the CRIM formula (Eq. 2.26). However, usually the depth of the reflecting interface is not known. Hence, a CO measurement usually provides too less information for a thorough estimation of soil water content. At least it needs to be completed by independent information obtained from boreholes or soil profiles or by a so-called common-midpoint measurement which is described in the following section.

### 4.3.2 Multi Offset: Common Midpoint and Wide Angle Reflection and Refraction

In a common-midpoint measurement (CMP) transmitter and receiver are moved away from each other in equidistant steps (see Figure 4.7). At each position a trace is measured. This way, the reflected signal can be measured using a number of different angles. The resulting radargram displays the travel time as a function of the antenna separation (see Figure 4.8).

Since air and ground wave travel directly between the transmitting and receiving antenna, there is a linear relationship between the travel time $t$ of each wave and the antenna separation $a$ with the constant of proportionality $\frac{1}{v}$:

$$t = \frac{a}{v}, \quad (4.3)$$

with $v = c$ for the air wave and $v = \frac{c}{\sqrt{\varepsilon}}$ for the ground wave. Due to their different velocities the slopes of both direct waves in the travel time diagram are different.

Consequently, the propagation velocity $v$ of the GPR wave through the soil can be determined directly from the radargram by estimating the slope of the ground wave. Using (2.18) one obtains the average relative permittivity and with (2.26) also the average volumetric water content. Since the ground wave travels near the soil-air interface it covers that soil section which is for example important for plant growth. The air wave travel time is usually applied during data processing as reference for calculating absolute travel times.
From a CMP measurement one can determine the reflector depth below the midpoint between the transmitting and the receiving antenna: the relation between travel time $t$ and reflector depth $d$ is given by Equation 4.1.

From the reflection hyperbolas displayed in the travel time diagram relative permittivity and reflector depth can be determined independently. Plotting the measured data in a $t^2-a^2$-diagram, leads to a linear relationship between $t$ and $a$:

$$t^2 = \frac{1}{v^2} a^2 + \frac{4h^2}{v^2}. \quad (4.4)$$

The propagation velocity of the electromagnetic wave can now be directly determined from the slope of line. The depth of the reflector can be directly inferred from the intersection of the line with the $y$-axis.

In contrast to a CMP measurement, in a Wide Angle Reflection and Refraction (WARR)
4.3 Measurement Setups

Figure 4.9: Wide Angle Reflection and Refraction

measurement (Figure 4.9) only the transmitting or receiving antenna is moved along the measurement line while the other antenna stays stationary.

In principle, a WARR measurement follows the same relationships concerning travel time as a CMP measurement. The difference is that the reflection point moves along the reflector. This is why a WARR measurement strictly is only applicable in the presence of horizontal or only slightly sloping reflectors and material properties are homogeneous.

In summary, CMP and WARR measurements provide more information than a CO measurement. The drawback of these techniques is the high measurement effort since both procedures only provide point information for a specific location. Hence, both methods are hardly applicable along long measurement lines.

4.3.3 Multi-channel GPR

In order to be able to conduct a measurement with acceptable effort and acquire almost as much information as in a series of CMP or WARR measurements, Gerhards (2008) developed a multi-channel GPR measurement technique. This new method combines the traditional CO and CMP measurement techniques. In this setup at least two standard GPR units, each consisting of a transmitting and a receiving antenna are coupled in a row at a fixed distance and are moved along the survey track (Figure 4.10). The multi-channel unit is able to acquire data from all available transmitter-receiver combinations. In the example given in Figure 4.10 this leads to four measurement channels which can be used to record common-offset radargrams simultaneously but with different antenna separations. The survey is almost as fast as a standard common-offset measurement with only one single antenna system.

In a setup build of two antenna systems the four available channels can, e.g., be combined as follows:

- **Channel 1** transmitter 1 combined with receiver 1 (T1R1)
- **Channel 2** transmitter 2 combined with receiver 2 (T2R2)
- **Channel 3** transmitter 1 combined with receiver 2 (T1R2)

Here, channels 1 and 2 use the standard common offset antenna separation $a_1 = a_2 = \text{const}$. The antenna separations for channels 3 and 4 ($a_3, a_4$) can be selected by the operator (Figure 4.10).

The optimal antenna separation is

$$a_{\text{opt}} = \frac{2h}{\sqrt{\varepsilon' - 1}}. \quad (4.5)$$

If no information about the measurement site is available one usually uses the rule of thumb $a_{\text{opt}} = 0.2h$, where $h$ is the desired penetration depth.

From a multi-channel GPR measurement it is possible to effectively estimate reflector depth $h$ and relative permittivity $\varepsilon'$ with minimal effort. The information can subsequently be used to determine the average volumetric soil moisture content $\theta$ using the CRIM formula (Equation 2.26). Here, at least two absolute travel times are required for one distinct measurement position.

$$h = \frac{1}{2} \sqrt{\frac{t_i^2 a_j^2 - t_j^2 a_i^2}{t_j^2 - t_i^2}} \quad (4.6)$$

$$\varepsilon = \frac{c^2 t_i^2}{4h^2 + a_i^2} \quad (4.7)$$

A multi-channel GPR measurement is kind of a moving mini-CMP measurement: The radagrams 1 and 2 (Figure 4.10) are shifted laterally such that the measurement points are consistent with those of channels 3 and 4. This way, one obtains three measurements at one single location with different antenna separations.

In order to obtain absolute values for relative permittivity and reflector depth, also absolute travel times are required which are initially not known from a radargram. Due to experimental difficulties, each radargram has an unknown offset which, however, can be determined from the theoretical travel time of the air wave $t_{\text{air}}$ using...


\[ t_{\text{air}} = \frac{a}{c} = t - t_{\text{off}}. \]  

(4.8)

Here, \( t_{\text{off}} \) is the unknown offset which has to be determined from the radargrams. It can be calculated from the travel time of the air wave at antenna separation \( a = 0 \). However, since it is practically impossible to measure the travel time at this distance, one has to find a different way to retrieve this value. For the measurement we consider here, this offset can be determined from a calibration measurement as shown in figure 5.4 (How?). After performing the offset correction (equation 4.8) it is possible to quantitatively analyze the measured radargrams.

### 4.4 Energy Loss and Penetration Depth

As already mentioned in section 2.1.4, the electromagnetic signal is attenuated by different processes on its way through the soil. Figure 4.11 gives an overview of the different processes that lead to a reduction of signal strength.

The largest amount of energy loss results from damping of free charge carrier movement. Under the assumptions made for equation 2.18, the material dependent attenuation is induced by the direct current electric conductivity \( \sigma_{\text{dc}} \) of the investigated medium. Depending on the traveled distance \( x \) the amplitude \( E \) of the electromagnetic wave decreases exponential with respect to its starting value \( E_0 \):

\[ E(x) = E_0 e^{-\beta x} \]  

(4.9)

For the loss constant \( \beta \) one obtains after the above mentioned simplifications

\[ \beta = \frac{\sigma_{\text{dc}}}{2 \epsilon_0 \sqrt{\varepsilon'}}. \]  

(4.10)

The higher \( \sigma_{\text{dc}} \) of the medium, the higher is the attenuation of the electromagnetic wave. In soils, electrical conductivity for example increases due to an increase in soil moisture content, clay content or amount of dissolved solutes in the soil solution.

The penetration depth of the electromagnetic wave

\[ \delta = \frac{1}{\beta} \]  

(4.11)

reduces with increasing electrical conductivity of the medium. For salt water the penetration depth is only \( \delta_{\text{saltwater}} = 1 \text{ cm} \).

In addition, so-called spherical losses occur which are caused by the field geometry of the measurement. The energy density is reduced due to geometrical spreading with the inverse of the square of the traveled path.
Scattering and diffraction of the electromagnetic energy at objects whose dimensions are in the same order of magnitude as the wavelength of the incident electromagnetic wave (Mie scattering) lead to a redirection of the energy which then cannot be registered any more by the receiving antenna. Energy losses are also induced as a consequence of reflection and transmission losses during each passage through a boundary. The transmitted fractions cannot be registered anymore by the receiving antenna. Due to the missing coupling of the antennas to the ground part of the energy is lost into space. These losses can be summarized as boundary losses.

4.5 Signal Resolution

The successful detection of underground objects or structures is primarily restricted by the resolution of the measurement. This is the ability to distinguish two nearby structures or signals which are temporally close to each other. For the spatial resolution the wavelength $\lambda$ of the electromagnetic signal is relevant. Are two reflectors separated by more than half a wavelength ($\frac{\lambda}{2}$) they are usually well distinguishable in a radargram. Under very good conditions, the signal resolution can reduce to about one fourth of wavelength ($\frac{\lambda}{4}$). From the relationship of the propagation velocity $v$ with the wavelength $\lambda$ and the frequency
4.6 Concluding Remarks

\[ \lambda = \frac{c}{f} \] it is obvious that the smaller the wavelength and the higher the frequency, the higher is also the spatial resolution of the measurement. As mentioned in section 4.4 a higher frequency leads to a shallower penetration depth. Hence, when planning a survey one always has to find an optimal setup for a potentially high penetration depth together with a high resolution of underground structures. Sometimes it is preferable to choose a deeper penetration depth and a lower resolution if deeper situated structures are to be investigated.

After equation 2.18 an electromagnetic wave travels slower in a wet soil than in a dry soil due to their difference in relative permittivity. This causes that structures can usually be resolved better in wet soils than in dry ones. Contrary, the signal attenuation is higher in wet materials which usually reduces the penetration depth in these measurements.

4.6 Concluding Remarks

GPR is one of the most often applied geophysical measurement techniques. A great advantage is the good applicability under most field conditions. Common offset and multi-channel measurements are fast and allow to efficiently and non-invasively explore large areas at scales ranging from several tens of meters up to a few kilometers. GPR is best suited for taking measurements in low loss materials like sand or gravel since they are well penetrable by radio waves. In fine textured soils like clay or loam or in soils with high electrical conductivity GPR is less applicable since the signals are attenuated too strongly.
4 Ground Penetrating Radar
5 Experimental part

5.1 Structure and aims of the experiment

The main goal of these experiments is to achieve a thorough understanding of the principles and applications of two geophysical measurement methods that have found widespread use for determining soil moisture contents.

This practical course comprises two parts: For part A, TDR measurements will be executed in the laboratory at the Institute of Environmental Physics. The aim of this part is to record and interpret reflected signals of electromagnetic waves in several media under different conditions. Measurements for the second part will be carried out at one of our test sites in the vicinity of Heidelberg, where you will head together with your supervisor on the second day. At that site, several different GPR measurement methods will be used. Also, some TDR measurements will be recorded for comparison. The evaluation of these measurements will fill the third and forth day of this practical course.

5.2 Guiding questions

Before starting with the experiments you should at least be able to answer the following questions:

Theoretical Questions

- How do electromagnetic waves propagate in matter? What parameters are needed to describe this propagation?
- Which processes lead to energy dissipation of an electromagnetic wave propagating in a certain medium?
- Which regions of the electromagnetic spectrum are used for measuring relative permittivities and why?
- How and why can one determine soil water content from relative permittivity?
- What are the basic principles of Time Domain Reflectometry? How can relative permittivities be determined from TDR measurements?
• What are the fundamental principles of Ground-penetrating Radar? How can GPR measurements be employed for determining relative permittivities?

Practical Questions

• What kind of different methods for GPR measurements are there and what are the (dis-) advantages of these methods?

• Which quantities can be determined by the different GPR measurements?

• With which method can the temporal offset $t_{\text{air}}$ (equation 4.8) be measured for the different channels?

• What are the similarities and differences between GPR and TDR based measurements?

5.3 Part A: Laboratory measurements using TDR

The first part of the experiments will be carried out in the laboratory at the Institute for Environmental Physics and will mainly deal with TDR measurements. In this section, the different steps of this part of the practical course will be introduced and explained.

5.3.1 Basics: Performing TDR measurements

The TDR measurements in this practical course are acquired using a TDR100 instrument (see fig. 5.1), manufactured by Campbell Scientific Inc. This TDR100 instrument is a computer controlled reflectometer, where the program PCTDR is used for data acquisition. This program also allows for a graphical representation of the reflected signal. Please refer to section 7.1 for the settings needed for this practical course.

For getting started, please execute the following steps:

1. Boot the measurement laptop under Windows and connect the TDR100 to a free USB or serial port using the corresponding connecting cable.

2. Open the data acquisition program PCTDR, e.g. via the link provided on the desktop.

3. Connect the TDR100 to a power source. Either AC or DC power input is possible. AC input is suitable for laboratory use, DC input will be used to operate on battery in the field. Please use the respective power cord. Caution! Ensure using the right polarity when connecting the plugs (black plug = negative polarity).

At first you should get thoroughly acquainted with the measurement setup. To this end,
please connect a TDR-sensor to the TDR100, activate the button *continuous update* and start a measurement.

![Figure 5.1: The TDR100 instrument](image)

You should now conduct a first qualitative analysis of the form of the signal in different media – like air, water or sand. What happens if you touch the sensor with your hand? *Print out at least one TDR trace in air and one in water for your report.*

### 5.3.2 Preparation: Calibration of TDR sensors

For a quantitative analysis of all subsequent measurements, the TDR sensors have to be calibrated first. This is achieved by recording two-way traveltimes (compare chapter 3.2) of the signal in at least two different media with different but well defined permittivities, which allows to associate every measured travel time uniquely with the respective permittivity based on equation (3.1). The best way for TDR calibration here is to use water and air, as these two media can be considered to represent the two ”extreme cases” for moisture content in natural soils.

Hence, you should record five traces (*why more than one?*) in air and and then five more completely submerged in completely desalinated water (”VE-Wasser”). Make sure, that the rod length is set to the right value in the PCTDR software.

Do not forget to determine the water temperature for correcting permittivities according to equation (2.24) during data evaluation.

### 5.3.3 Measurement: TDR signals from a sand column

In this part of the experiment, the just calibrated TDR sensors will be used to quantitatively measure different water contents in a sand column, the according experimental setup is pictured in figure 5.2. The water gauge in this sand column can be tuned to different heights, therefore inducing different water contents which can be measured with a TDR sensor.

At first, insert a TDR sensor with 30 cm rod length vertically into the initially dry soil column. Please take extra care not to introduce any airgaps along the rods while insert-
5 Experimental part

Figure 5.2: Overview of the measurement setup for the soil column

ing the sensor, as this will severely impair the measurement and could yield completely worthless results. Then the water gauge is to be risen slowly from the bottom of the soil column until complete saturation has been reached. This can be done by adjusting the height of the water container; hanging the water container higher will raise the water gauge in the column due to the increase of hydrostatic pressure. Record one TDR trace after every rise of the water gauge of 5 cm, you can judge the progress from the scale on the column itself. The final trace should be recorded after the soil column has reached complete saturation. To ensure that the PCTDR-window can show the complete signal over the whole measurement process, please use the following parameters: \textit{start}: 3.50, \textit{length}: 2.80.

Then, put the water container onto the ground, so that the water can slowly flow back out of the column and record again one TDR-trace after every 5 cm drop of the water gauge.

5.3.4 Measurement: Assessing the Influence of conductivity

As has been described in section 3.4, the shape of the TDR signal is influenced by the electric conductivity of the measured medium along the TDR sensor rods. In this part, this influence is to be qualitatively assessed. To get a feeling for this effect, a set of TDR traces is to be recorded in water exhibiting different salt concentrations as follows:
1. Fill a bucket with 10 l of completely desalinated water.

2. Connect a TDR sensor with 20 cm rod length to the TDR100 and adjust the following settings of the PCTDR software under the menu waveform: \( \text{start} = -2.00 \), \( \text{length} = 202.00 \).

3. Record the TDR signal when the sensor is held vertically in the bucket.

4. Then successively add 1 g of salt to the bucket, stir thoroughly until complete dissolution and record a TDR trace afterwards, until a total of 5 g have been dissolved. You should have recorded six TDR traces for this part of the experiment.

5.4 Part B: Field measurements

This section describes the field experiments which will be carried out at one of our test sites in the vicinity of Heidelberg. Here, different GPR techniques will be applied and some TDR measurements will be recorded for comparison.

5.4.1 Equipment checklist

Before heading into the field, make sure that all needed equipment is in place and thoroughly stored in the respective equipment boxes. For the experiments here, the 200 MHz antenna system will be used. Locate and pack the following items:

1. Panasonic measurement laptop and network cable
2. Laptop carrier "backpack"
3. \( 2 \times \) 200 MHz antennas
4. DAD-control unit
5. distance-measuring wheel and air-WARR adapter
6. Antenna remote control
7. \( 2 \times \) fully charged 12V batteries
8. connecting cables: power cable for DAD-control unit, DAD-to-front-antenna, front-to-back-antenna
9. pulling cables and rope for connecting the antenna boxes
10. toolboxes: IDS auxiliary box and the general tool box
5 Experimental part

Figure 5.3: GPR antenna system setup

11. TDR100 instrument and connecting cables for DC power input
12. different TDR probes, at least one probe with 10 cm, 20 cm, and 30 cm rod length
13. equipment for inserting and extracting TDR probes in the field
14. soil thermometer
15. tape measure
16. practical course field book

5.4.2 Measurements

All measurements will be carried out along a 50 m long transect. At first, a multichannel measurement (refer to chapter 4.3.3) will provide an overview of the subsurface structure. Later this data will be used to determine the depths of identified reflectors and the average water contents to these reflectors. For calibration purposes, some additional traces have to be recorded in a specified way at the end of the profile in order to determine the time-zero offset of the different channels (cf. to section 4.3.3 and figure 5.4).

For comparison, several CMP (cf. to chapter 4.3.2) and TDR measurements will be carried out.

Please execute the measurement steps as follows:

1. In preparation of the measurement, select a profile of approximately 50 m length
for the multichannel measurement and mark it by a string.

2. At first, the GPR instrument system (figure 5.3) has to be carefully assembled. Make sure, that all components (antenna-boxes, distance measuring wheel, battery, laptop) are connected to the DAD-control unit, which is used to control the antennas using the software K2 and for digitizing the recorded GPR data. Having assembled all the components, please boot the measurement laptop. Then, switch on the DAD-control unit by pushing the red button on the unit until the blue light is turned on. Afterwards, K2 can be started via the link provided on the desktop. For the most important settings as well as information on the general usage of K2, please refer to section 7.3. Most importantly, you can find instructions of how to record GPR radargrams there. Find a way to identify the channel numbering of the K2 software with the different channels shown in figure 4.10.

3. Decide for an appropriate antenna separation (how?), adjust the antennas accordingly and carry out a multichannel measurement along the just prepared line. Ensure you have chosen a reproducible starting point and pay attention to an adequate pulling speed.

4. At the end of the multi-channel profile, add a calibration measurement as shown in figure 5.4 to the radargram. This allows for an instructive way to determine the time-offset $t_{off}$ (how?), needed for calculating the absolute permittivity and water content during later evaluation. Do not forget to note down the

Figure 5.4: Radargram of a calibration measurement at the end of the multi-channel profile: part (i) last part of the profile; (ii) some additional traces at the used antenna separation at the end of the profile; (iii) traces recorded with antennas turned sideways; (iv) adding more traces in same position as (ii) again; (v) mini-WARR measurement: pulling the rear antenna close to the front antenna (vi) some more traces recorded in final position after (v). Also, the first minimum of the signal is indicated by the colored lines in each section.
5 Experimental part

antenna distance for each channel (the internal antenna are 0.19 m for the IDS 200 system and 0.14 m for the IDS 400 system).

5. Make a rough plot of one of the just recorded data for taking a closer look. What kind of signals show up? How does this tie in with the current field conditions? Try to understand the different types of signal which you can identify. Do you recognize a ground wave signal? Are there any reflections to be seen? Depending on your judgement and the encountered field conditions, decide to either investigate a ground wave signal (execute step 6) or a reflected signal (directly skip to step 7) more closely.

6. If you decide that you want to take a closer look at the groundwave signal, select an about 3 m long stretch along the profile, where the signal seems to be interesting. Try to characterize this stretch as detailed as possible by additional TDR and GPR measurements:

a) CPR: Carry out at least two WARR and one CMP measurement in the vicinity of this stretch. You do not have to change the K2-settings for WARR measurements. Simply disconnect the antennas, put the first at a fixed position, start a new profile and pull the second antenna straight backwards. Make sure, that the distance measuring wheel turns properly and even more so that the antenna connecting cables are not overstretched!
For the CMP measurement, replace the distance measuring wheel by the remote control and change the settings in the K2 software (section 7.3.2). Arrange the antennas around the intended mid-point, write down the starting antenna separation and record a trace by pushing the button on the remote control. Then, successively increase the antenna distance in steps of 10 cm by moving each antenna back by 5 cm until the extent of the cables do not permit a further increase of the antenna separation. Record one trace per antenna separation.

b) TDR: First, carry out measurements using three probes with rod lengths of 10 cm, 20 cm and 30 cm at at least five points along the three meter stretch. Always double check having entered the right rod lengths in PCTDR, adjust the width of the measurement window reasonably to the signal. Also, measure the soil temperature at every measurement point with the provided soil thermometer for later temperature correction. Then, use the 10 cm probe to record a trace every ten centimeters along that stretch for judging small-scale variability.

7. Should you decide to take a closer look at a reflection present in the just recorded data, identify 2-3 interesting points along the measurement line from the measurements and place markers at the respective locations along the long. Add at least the following measurements:

a) GPR: Execute a CMP measurement at each of the just identified points. To do that, please replace the distance measuring wheel by the remote control and change the settings in the K2 software (section 7.3.2). Arrange the antennas
around the intended mid-point, write down the starting antenna separation and record a trace by pushing the button on the remote control. Then, successively increase the antenna distance in steps of 10 cm by moving each antenna back by 5 cm until the extent of the cables do not permit a further increase of the antenna separation. Record one trace per antenna separation.

b) TDR: Carry out measurements using three probes with rod lengths of 10 cm, 20 cm and 30 cm at each identified point. Record some additional traces with the 10 cm probe to get a feeling for small-scale variability. Always double check having entered the right rod lengths in PCTDR, adjust the width of the measurement window reasonably to the signal. Also, measure the soil temperature at every measurement point with the provided soil thermometer for later temperature correction.

8. Having recorded all the intended data, check once more that you have all information needed for evaluation (measurement locations, antenna separations, temperatures...), then carefully pack up the instruments and head back.

5.4.3 Wrap up tasks

After returning from the field, all equipment has to be cleaned and stored in its proper place. Used batteries as well as the measurement laptop have to be connected to their charging units. If necessary, unusual events and possibly encountered problems should be written down into the field book, especially if it could affect the next crew using the antennas.
5 Experimental part
6 Evaluation of the measurements

The evaluation of the experiments carried out in this practical course should at least include a detailed treatment of the following points.

6.1 Part A: Laboratory measurements using TDR

6.1.1 Qualitative description of TDR signals

Describe the qualitative characteristics of the TDR signal and its shape when measured in different media. Discuss in detail the traces acquired in air and water. What are the key differences and similarities and how can they be explained?

6.1.2 Calibration of TDR sensors

For evaluating all subsequent measurements, the values for two-way travel times and according permittivities as determined during the calibration measurements for each sensor have to be stored in a calibration file. Table 6.1 shows the structure of such a calibration file. The names of the TDR-sensors have to be stored in column name. In the next two columns, cable and sensor, the cable-length and rod-length of the respective sensors have to be entered. The remaining eight columns are for the measured travel times $t_a$ and $t_w$ and according permittivities $\varepsilon'_a$ and $\varepsilon'_w$ with their respective errors. These values have to be determined as follows:

1. Determine the theoretical permittivity for water at your measurement temperature and the pertaining error using equation (2.24).

2. Use the TDR-evaluation program to retrieve the two-way travel times of the signal from all recorded calibration measurements in air and water for each sensor (Cf. to

<table>
<thead>
<tr>
<th>key</th>
<th>name</th>
<th>cable</th>
<th>sensor</th>
<th>epsilon (air)</th>
<th>error</th>
<th>traveltime (air) ns</th>
<th>error</th>
<th>epsilon (water)</th>
<th>error</th>
<th>traveltime (water) ns</th>
<th>error</th>
</tr>
</thead>
<tbody>
<tr>
<td>TDR</td>
<td>C03</td>
<td>2.05</td>
<td>0.3</td>
<td>1.0</td>
<td>0.0</td>
<td>1.311</td>
<td>0.004</td>
<td>79.227</td>
<td>0.018</td>
<td>9.571</td>
<td>0.012</td>
</tr>
<tr>
<td>TDR</td>
<td>KB8</td>
<td>1.96</td>
<td>0.2</td>
<td>1.0</td>
<td>0.0</td>
<td>0.992</td>
<td>0.021</td>
<td>78.792</td>
<td>0.358</td>
<td>6.484</td>
<td>0.021</td>
</tr>
</tbody>
</table>
3. For each sensor, use these travel times to calculate the respective averages for $t_a$ and $t_w$ as well as the pertaining standard deviations.

4. Adjust the according values in the existing calibration file `probes_calib.dat` and save your changes.

### 6.1.3 Evaluation of TDR signals from the sand column

Graphically represent the TDR traces while the water gauge in the sand column was on the rise. Discuss the changes of the signal characteristics. Determine the water content from measurements while the gauge was on the rise and on the fall. Plot the respective water contents vs. the according heights of the water gauge. What conclusions can be drawn from this diagram?

### 6.1.4 Assessing the Influence of conductivity

Plot all six recorded traces into a joint diagram and label each signal accordingly. Discuss the influence of conductivity on the shape of the TDR-signal.

### 6.2 Part B: Field measurements

#### 6.2.1 Evaluation of measured data

The evaluation is done with two programs which are described in section 7.4.

1. First, the temporal offset for each channel has to be evaluated, using the reference measurements at the end of the multichannel measurement. To this end, determine the apparent travel time of the airwave at the antenna separation $a = 0$ for each channel. You have to do this in different ways for the cross channels and the internal channels (how?). Use the tools described in section 7.4.1 and 7.4.2.

2. Next, evaluate the measurement according to your decision in the field:

   a) If you investigated the ground wave signal, first execute a picking of the direct ground wave signal in one of the multichannel radargrams using the graphical interface PickniG (see section 7.4.1), then calculate water contents along the whole profile with an according PiG evaluation script, using the methods described in section 7.4.2.
6.2 Part B: Field measurements

b) For each WARR / CMP measurement, derive the water content using the direct ground wave signal. Again, use the tools in sections 7.4.1 and 7.4.2.

c) Next, evaluate the TDR measurements taken in the field. Determine the water content from all recorded traces. (Cf. to section 7.2 for further instructions).

d) Finally, plot all GPR and TDR derived water contents from the small three meter stretch into an appropriate diagram. Use Matlab, Octave, Gnuplot, Openoffice or whichever tool you are familiar with.

3. If you investigated a reflection signal:

a) Evaluate the multichannel measurement according to the steps described in section 7.4.2.

b) For each CMP measurement, derive (i) the water content using the direct ground wave signal and (ii) the water content and the reflector depth using the reflected signal. Again, use the tools in sections 7.4.1 and 7.4.2.

c) Finally, evaluate the TDR measurements taken in the field. Determine the water content from all recorded traces. (Cf. to section 7.2 for further instructions).

6.2.2 Interpretation of acquired data

1. Each radargram of a multichannel measurement is equivalent to a normal common offset measurement. Qualitatively discuss one of the two cross-box radargrams. Which conclusions can be drawn about the subsurface structure?

2. Compare the TDR derived water contents with the values derived from the CMP and WARR evaluations. Discuss possible differences, taking into account different sensor lengths and the scope of the different methods for determining soil moisture contents.

3. For the focus on ground wave: Discuss in detail the results of the measurements along the three meter stretch. How do you explain differences or agreements between the different methods? What does this tell you about the representativeness of the respective methods? Can you deduce anything about a depth of sensitivity of the recorded ground wave measurement?

4. For the focus on a reflection: Compare the water content and reflector depth values derived from the CMP measurements with the respective values from the multichannel measurement. How do you explain differences or agreements between the different methods? What does this tell you about the representativeness of the respective methods?
6 Evaluation of the measurements
7 A guide to the programs and algorithms used for data recording and evaluation

7.1 Recording TDR-signals using PCTDR

![Screenshot of the PCTDR software]

Figure 7.1: Screenshot of the PCTDR software

In this practical course, the program "PCTDR" is used for recording TDR traces. Figure 7.1 shows a screenshot of the software. The following section contains an introduction into the usage of the software and a description of the settings needed for carrying out the experiments in this practical course.
Introduction to the parameter selection boxes

- **Cable**

  \( V_p \) This value denotes the ratio between the propagation velocity of an electromagnetic wave within a certain cable and the propagation velocity in vacuum. In our case, this value should always be kept at 1.0, meaning that we neglect any cable induced effects.

- **Waveform**

  **Average** This parameter defines how many measurement values are automatically stacked for noise reduction during the measurement process. You should use a value of at least 4, higher values are recommend to counteract a high noise level.

  **Points** This value describes the number of points used to digitize the reflected signal as shown in the measurement window. For water content measurements, a value of 251 data points is suitable. Using this setting, the x-axis is discretized into 250 intervals, since the first data point denotes a relative point zero, being identical to the value entered in the field \( \text{start} \).

  **Start** The signal is shown in the measurement window for all x-values greater than this value. For determining water contents, this start value should be chosen such that the signal before the reflection of the sensor head is shown for about 0.5 units. This reflection which is due to the transition of the 50 Ohm-cable to the impedance of the sensor head is characterized by a sudden change of the reflection coefficient from the zero line.

  **Length** This value defines the cutoff of the signal. The signal will be shown from the \( \text{"start"} \) value until the here entered value added to that start value. The value in \( \text{"length"} \) has to be set appropriately for each sensor length. For measuring water contents, the whole response of the soil has to be discernible.

- **Probe**

  **Length** in this field, the length of the sensor rods has to be entered.

  **Offset** This value denotes the fraction of the sensor rods not being inserted into the medium that is to be measured. For the experiments carried out during this practical course it should always be zero.

- **Graph**

  **Get Waveform** This button starts a measurement, the retrieved trace will be displayed in the measurement window. If selecting the option \( \text{"continuous update"} \), the signal will be continuously updated as fast as possible. To cancel the continuous updating, simply deselect this option. The update rate depends
on the setting of the parameters under Waveform and the cable length and can take between some seconds and up to one minute.

**Capture Overlay** This option allows to simultaneous display two different signals for direct comparison. To that end, record the first signal by pressing the button Get Waveform and store it through pressing Capture Overlay. Then a second signal can be recorded. To display the stored signal, select the option Overlay Visible.

- **further settings**

  The scaling of the x- and y-axis can be changed through Adjust Axes Range.

  A double-click directly onto the signal opens a new window, where line-type as well as thickness, color and style of the line displaying the signal can be adjusted. Using the button Data in this new window, a table with the current signal’s data can be accessed.

**Menu bar entries**

- **Menu ”File”**

  **Save Configuration** Saves the current configuration in the fields Cable, Waveform and Probe to a .wfd-file.

  **Load Configuration** Loads a .wfd-file with configurations for the fields Cable, Waveform and Probe.

  **Save ASCII Waveform** Saves the current signal as displayed in the signal window to a .dat-file. This file contains the 251 values of the signal as well as the header, where the configurations for the settings in Waveform Average, Cable Vp, Waveform Points, Waveform Start, Waveform Length, Probe Length and Probe Offset are stored.

  **Print Graph** Sends the signal which is currently displayed in the measurement window to the standard printer.
7.2 Evaluation of TDR signals

Evaluation of the TDR data is carried out under Linux. For using the commands as described below, open a terminal window and go to the directory where the trace files have been stored.

The basic command line is

\texttt{evaltrace \textless probename\textgreater \textless filename\textgreater |\textless filenames\textgreater ~ \textbar ~ --\textless options\textgreater}

The \texttt{probename} has to be replaced by the name of the TDR sensor used for the respective measurement (as stored in the calibration file), for \texttt{filename} the path to the trace file which is supposed to be evaluated from the current directory has to be entered. Also, more than one path for traces acquired with the same sensor can be given. An overview over all the possible options can be displayed in the terminal window through using

\texttt{evaltrace --help}

The most important options are:

- \texttt{--time} display the two-way travel time in nanoseconds.
- \texttt{--epsilon} display the evaluated relative permittivity.
- \texttt{--watercontent} display the evaluated volumetric water content.
- \texttt{--all} Display all evaluated values (travel time, relative permittivity, temperature and volumetric water content).
- \texttt{--temp=<T>} The temperature at which the data are evaluated is set to \texttt{T}, where temperature has to be entered in °C.
- \texttt{--caldat=<S>} The calibration file can be found under \texttt{S}.
- \texttt{--result=<R>} The evaluated results are saved to a text file under the path \texttt{R}. They will simultaneously be displayed in the terminal window.

Furthermore, the evaluation algorithm uses the predefined values $\phi = 0.37$ and $\varepsilon_s = 5$.

If needed, please refer to the TDR manual for further advanced settings.

To make plots of the evaluated TDR signals use the program \texttt{plot_fit_and_derivative}. You can get plots of a trace, its derivative and the fitted parabolas (figure 3.2). Use the terminal command \texttt{plot_fit_and_derivative --help} to learn more about the program.
7.3 Recording GPR-data using K2

7.3.1 Acquiring a multichannel measurement

After starting the K2-software, the start-up window as pictured in figure 7.2 is shown. Before the actual measurement can be carried out, the system has to be properly calibrated. This process is executed as follows:

- Click on the button *Configuration* and select the configuration setting *Praktikum* from the window which opens.

- Clicking on the symbol for the data channels in the lower right of the main window opens a secondary window displaying the current signal of this channel. The signal of every channel has to be adjusted such that it is fully displayed in the measurement window (compare figure 7.3). For the longer channels, where the signal is comparatively weak, this can take some exercise.

- Clicking on the program symbol (*K2*) on the upper left of the main window opens the *Advanced Settings*-menu. Please deselect the option *Background removal* in that menu.

- Then, click on the button *Start calibration* and subsequently turn the distance measurement wheel of the antenna system, until a new window opens which is shown in figure 7.4.

- In this window, press *New survey* and enter the name for the folder that should later
7.3.2 Differences for performing CMP-measurements

While acquiring a CMP-measurement, the remote control is used for triggering data acquisition instead of the distance measurement wheel. For using the remote control, also some settings in the software have to be changed.

- Change the configuration setting to *Praktikum-CMP*.
- In the *Advanced Settings*-menu, change the wheel setting to *Auto stacking*. Closing the advanced setting menu will then automatically start the calibration.
- Before actually starting the measurement, you then have to change the wheel setting in the *Advanced Settings*-menu back to *Wheel driven*.
- Then, whenever the antennas are brought into the intended distance, the corresponding trace is acquired by pressing the button on the remote control exactly once.

7.4 The Evaluation of Ground Penetrating Radar Data

The whole evaluation of the radargrams will be done under a linux system. You have to use two programs sequentially for the evaluation: *PickniG* and *PiG*. Both of these programs were developed in the soil-physics group of the institute of environmental physics Heidelberg and you can find a description in the following. To get the programs started you have to use a terminal and type in the name of each program (see below).
7.4 The Evaluation of Ground Penetrating Radar Data

Figure 7.3: Correct setting for the signal of a measurement channel

Figure 7.4: Acquisition selection window
7 A guide to the programs and algorithms used for data recording and evaluation

7.4.1 The Evaluation with PickniG

PickniG is a graphical front end which provides some basic processing steps (filters and automatic picking) for radargrams. Use PickniG to reduce noise in the data by special filters and to mark characteristic structures (such as reflectors in CO measurements or airwave signals in WARR measurements) by picking.

PickniG uses the units meters for spatial coordinates and nanoseconds for the time variable.

You can save the processed data and the marked structures in on file type, the PickniG data type. This file type can be read by PiG and you can apply further processing steps.

Calling PickniG via the commando line of the terminal, a window as pictured in Fig. 7.6 should pop up. The basic functions for the first processing steps are:

File → Import Radargram All measured radargrams can be imported into the PickniG-environment via this menu-option. (Note: All measured GPR data for a single survey can be find in a .zon-directory. Usually you can find files named laa10001.dt to laa40001.dt. They contain the measured data for the first line from channel one to four.)

File → Save PickniG Data File With this menu-option you can save the current state of the evaluation in a PickniG data file, identifiable via the extension " .pg" .

File → Open PickniG Data File This opens an already saved PickniG Data File.
7.4 The Evaluation of Ground Penetrating Radar Data

Figure 7.6: The PickniG-window. On the top you can call functions and set some image properties, while the radargram is shown in the middle left. The window ”Component View” shows all opened radargrams with processing steps and data structures (like picks). If you load plug-ins, corresponding fields will show up on the bottom with which you can set parameters of the plug-ins.

**Edit → Remove All Marker** This menu-option removes all markers. They are necessary especially for the later picking-procedure.

**Edit → Delete Selected Entities** An entity can either be a radargram or a picked radargram feature. With this menu-option you can delete selected entities on the right hand side of the window.

**Plug-ins →** Here, you can choose which filters or processing steps you can apply on the radargram. If one plugin is selected, it will be occur with all necessary input boxes for the required parameters in the bottom line of the window.

**Dewow** The dewow filter is a high-pass filter [Gerhards (2008)]. It is at least required for illustration purposes, because a measured radargram always has a constant amplitude offset. This should be removed to obtain a baseline at the zero-amplitude. The parameter determines the amount of frequencies which will pass the filter.

**Shift** This function shifts the values of the time and position axis by the value given in the variable $\Delta t$ and $\Delta x$ respectively. Here, only the internal data are affected, but there is no graphical change unless no picking was done before.

**Pick** Using this function, a characteristic structure (like a reflection or a direct wave) in the radargram can be tracked throughout a radargram (‘picked’).
The resulting ‘pick’ then denotes the change in arrival time of this specific wavelet feature throughout a radargram. This pick can then be used as an input for evaluating the travel times of the corresponding wave and in turn e.g. water contents.

The picking algorithm provided here tracks specific wavelet features (like zero crossings or maximums) to draw a line along these features in between two markers. Hence, first select the ‘marker mode’ and set two markers on the structure of the radargram you want to pick. Then you have to adjust five parameters for the wavelet feature to be picked: The **Mode**-parameter denotes the mode of the picking procedure. A value of 0 would pick zero crossings. Positive modes try to pick positive values and negative modes focuses on the negative amplitudes. The modes +1,+3 and -1,-3 try to pick the corresponding maximal values, but in different ways. Where the modes +3/-3 tends to be more accurate, +1/-1 is more stable.

The **Thres**-parameter is relevant for the modus +1/-1. It denotes a percentage threshold value after which the next leading sign change of the derivative of the amplitude is interpreted as a maximum value.

The parameters **Tback** and **Tforward** define a time interval (in [ns]) for the picking algorithm within which the chosen wavelet feature is tracked throughout the radargram. If these values are chosen too small, the algorithm will not be able to find the chosen wavelet feature on the following trace, if the interval becomes too large, the picking algorithm will jump to neighboring wavelet features or even other wavelets.

The parameter **DX** can be used to obtain a pick from an averaged trace using an averaging distance denoted by this parameter. It is recommended to set this value to 0.0.

Finetuning the picking parameters can require some exercise to achieve the desired results. So take some time to play around with different settings.

All other functions can be discovered by everybody on its own.

### 7.4.2 The Evaluation with PiG

PiG is a scripting language for processing measured radargrams or preprocessed PickniG data files. The idea is that a script (ASCII-file) with specific commands/functions and corresponding parameters is read by the program `gpr_eval`. This program executes the commands subsequently. To run a script, type in the command `gpr_eval` with the script-name as an additional parameter in the terminal (For example: `gpr_eval pig_script.dat`).

PiG is used for two major purposes: To process data and to plot results. Some processing steps among others are the identification of picks, linear regression of picks, and evaluation of multichannel measurements. For this practical course, appropriate scripts are provided. But, they have to be adapted to evaluate your own dataset by setting the variables in the scripts. These variables correspond to the green expressions below. The commands of the scripts are explained in the following. PiG uses the units meters for spatial coordinates.
7.4 The Evaluation of Ground Penetrating Radar Data

and nanoseconds for the time variable. The commands of the scripts are explained in the following.
For more detailed questions, you can also take a look at the PiG manual, which can be downloaded from http://www.iup.uni-heidelberg.de/institut/forschung/groups/ts/soil.physics/tools/PG-package/Downloads/.

Evaluation of Direct Waves from a WARR- or a CMP-Measurement

For the evaluation of direct waves, pick them in PickniG and save the processed radargram with the pick as a .pg file. Then make the necessary adjustments to the evaluation script which is described in the following and run it with PiG.

RADARGRAM 1 <pg-file> <number>
Reading a radargram from the pg-file. You have to replace pg-file by the file-path to the radargram that is to be evaluated (enter the file-name without its file-extension .pg). The parameter number should be 1, if only one radargram can be found in the pg-file.

SHIFT <x> 0
Spatial shift of the radargram. If the radargram was not shifted in PickniG, you should do it here. The parameter x must be the antenna separation at the beginning of the measurement.

PICKING 1
This command denotes that a pick is allocated. All following commands beginning with % refer to this pick.

% GET <pg-file> <num1> <num2>
With this command, you can read a pick from the pg-file. Here, you must give the number num1 of the radargram to which the pick belongs. The second number num2 is the number of the pick. If there is only one radargram and one pick in the pg-file both values must be 1.

% SHIFT <x> 0
Spatial shift of the pick. If you have not shifted the pick in PickniG, you should shift the pick here. The parameter x must be the antenna separation at the beginning of the measurement. This is necessary to obtain the right travel time offset value.

PICKING 2
This command allocates another pick. In this pick we want to store the result of the linear regression which is performed on the first pick.

% CALC VELOCITY 1 output=<name>
This command performs a linear regression (or in other words fits a linear function to the pick) on the first pick, indicated by the number 1. The results are returned in the shell and in the output-file. You have to give the name of the output file. The results of the evaluation are the velocity of the wave, the corresponding relative
permittivity and the travel time offset.

**Evaluation of a Multi-Channel Measurement**

For the evaluation of a multi-channel measurement, all relevant structures (direct waves and reflections) in the radargrams should be picked via *PickniG* and stored in a pg-file. Here, you should only pick a structure if this structure occurs in all radargrams. The evaluation of the picks must be done with *PiG*, using the commands explained below.

RADARGRAM 1 <pg-file> 1
Reading the first radargram from the pg-file.

PICKING 1
% CONST <travel time>
Here, you have define a structure to which all other structures are referred to. The candidate for this structure is the air wave, even if it might not be present in the radargram. Calculate the travel time of the air wave + the temporal offset and replace travel time with that number.

PICKING 2
% GET <pg-file> 1 1
With this command, you can read the first picked reflector from the first radargram of the pg-file. If there are further picks for the same reflector, you should repeat this command with different numbers at the end.

SHIFT <x> 0
If the radargram was not shifted in *PickniG*, you should do it hear. The parameter x is a length. It must set in a way that measurements at the same location with different channels have the same distance value in the radargram. (Without the correction, the start of each radargram has a distance value of 0.0 m.)

AMPLIFY

EQUALIZE
The last both commands can be applied for illustration purposes, in the case that the graphical output must be enhanced.

.... The radargrams and the picks for the other channels must be read in the same way.

MULTICHANNEL ALL
This statement marks that all following commands belong the multi-channel evaluation. Here, no modifications on the radargrams can be performed.

USE_RADARGRAM 1 PICK 1,2 ANTSEP <a1>
7.4 The Evaluation of Ground Penetrating Radar Data

USE_RADARGRAM 2 PICK 1,2 ANTSEP <a2>
USE_RADGRAM 3 PICK 1,2 ANTSEP <a3>
USE_RADGRAM 4 PICK 1,2 ANTSEP <a4>
With these four commands you assign all data which shall be used for the multi-channel evaluation. Here, for each radargram, you must state which pick corresponds to the air wave and to the reflected wave. Furthermore, the antenna separation (a’n) for each channel must be given.

EVALUATION 1 RADARGRAMS 1,2,3,4
Now, the multi-channel evaluation will be performed. All channels will be used in this example.

RUNMEAN <traces> If the result of the evaluation is too noisy, one can apply a running average filter. The window for this filter is given by the number of traces.

Data Output with PiG

In order to draw radargrams and the reflectors with PiG, you can use the following commands.

PLOTTING <file-name>
This commands initializes an environment for the graphical output. Here, a file named file-name.eps will be created.

PLOT_RADARGRAM <n> TYPE density 1 <p> TRANSFORM 1
The radargram with the number n will be plotted as a density type format (contour plot). The parameter p ∈ (0, 1) is relevant for the contrast. The ending of this command line denotes, that the amplitudes are transformed in a logarithmic way in order to visualize low amplitudes. This will not be performed, when you write 0 instead of the 1.

SET_LINES COLOR HSB 0.3 1 1 THICKNESS 0.5 DASH -1
This command line set the color, the thickness and the draw type (dashed or not dashed) for the following plot of a reflector.

PLOT_REFLECTOR <radar-num> <refl-num>
The reflector with the number refl-num of the radargram with the number radar-num will be plotted.

SET_LINES COLOR G 1 THICKNESS 0.1 DASH -1
This commands sets the color, the drawing thickness and the draw type back to the initial values. It is necessary if further plots will be performed afterwards.

In order to plot the results of a multi-channel evaluation, you can use the following commands.
A guide to the programs and algorithms used for data recording and evaluation

PLOTTING <file-name>
This commands initializes an environment for the graphical output. Here, a file named file-name.eps will be created.

SET_Y_AXIS <val1> <val2>
The boundaries of the y-axis for the plot must are defined at this place.

SET_THETA_CALCULATION temp=<T> epsSoil=<E> poros=<P>
If you want to plot the water content, you must set the parameters for the CRIM-formula Eq. 2.26 before you plot it, otherwise you can neglect this command line.

PLOT_EVALUATION <n> <solution> USING_RADARGRAM <m>
This commands plots a result of the multi-channel evaluation n. The parameter solution must be set to depth, epsilon or theta to obtain the reflector depth, the relative permittivity or the water content, respectively. The parameter m determines from which radargram the x-axis is taken.

OUTPUT_EVALUATION <output-file> <n> depth epsilon theta
If you are additionally interested in the numerical values for the reflector depth, the relative permittivity and the water content of the n’s multi-channel evaluation, you can use this command. The values will be stored in the file output-file.
Bibliography


