Field and Laboratory *ad hoc* Calibrations of Virrib and ThetaProbe Dielectric Sensors for Soil Moisture Measurements

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Abstract: For the research of irrigation optimization and nitrate leaching it is important to know the short-term soil moisture variation during percolation episodes as well as its seasonal pattern. Dielectric soil moisture sensors Virrib (AMET – Consortium) and ThetaProbe ML2x (Delta-T) were used for this purpose over several years for measuring soil moisture content at hourly intervals in Valečov (49°38’40” N, 14°30’25” E, 461 m a.s.l.), Czech Republic, in a deep loamy Stagnosol soil underlain by weathered paragneiss. One-point field calibration was made each spring at the time of sensor installation over three (for Virribs) or two (for ThetaProbes) consecutive years by taking sensor readings and soil samples (at least one 100 cm^3 core sample near to each sensor) in parallel. A supplementary check was then made in the laboratory by taking readings of individual sensors, inserted into pre-made loamy-sand mixtures with various moisture contents. During both the field calibration and the laboratory check, the readings were taken manually, using either the AMET hand-held meter or the EMS ModuLog datalogger. The results suggest that the average slope of the secondary Virrib calibration curve (defined as the plot of y = sensor readings in terms of moisture content vs. x = soil moisture content determined gravimetrically) is near to unity, but the offsets are quite large and vary from probe to probe. The axial zone of influence of the Virrib sensors is up to about 30 cm, as it follows from both laboratory and field observations. The results of the laboratory check of Virribs were biased, because the volume of the soil was not large enough and the soil had different dry bulk densities at different moisture contents. The field secondary calibration curve of ThetaProbes appears to be roughly linear, in contrast to the laboratory calibration curve, because of absence of very low moisture contents in the field. If the same calibration line is applied to several different depths, then its slope is statistically significantly lower then unity, due to the dependence of ThetaProbe readings on the soil bulk density. The overall accuracy of the sensors and its components due to different factors is estimated from the statistics of repeated measurements.

Keywords: Virrib; ThetaProbe; one-point; loam; loamy sand; zone of influence; bulk density; offset; FertOrgaNic

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For solution of many practical and applied research problems, one often needs to know how water and solutes in the soil move, sometimes on a very detailed spatial and temporal scale. It is therefore necessary, among other things, to continuously monitor soil moisture content. Dielectric sensors of various types are commonly used for this purpose. They are very sensitive to changes of water content in their immediate vicinity but also to other factors. It is not possible to rely blindly on their data. However, in practically oriented projects, it is often not enough time and labour to carry out sophisticated calibrations or verifications of the sensors and other equipment used. In such cases, the checks and calibrations made are often not systematic enough. Their results, seen at first glance, often discourage people from using dielectric and indeed any other soil moisture sensors. Unconventional ways of evaluation may then be needed to make use of such data. This paper provides an example of this approach.

As for the terminology describing various methods, we adhere to that presented by Muñoz-Carpena (2004). The methods for which the results are reported below are referred to as the phase transmission method (Virrib probes) and the amplitude-domain reflectometry (ThetaProbes). Our terminology of calibration is the same as that used by Kučera *et al.* (2007). Namely, the output of the probe is an electrical quantity Q (in our case it is either the direct current I or the direct voltage V), which can be related in some way to the moistness of the medium, M, usually, and in our case, the volumetric moisture content of the soil, θ (m^3/m^3). This relation, $M(Q)$, is referred to as a calibration curve. If the calibration curve has been provided by the probe manufacturer or derived from the manufacturer's data, we call it primary calibration curve. If it is believed to apply to all probes of a certain sort, it can be referred to as the universal calibration curve. Any user of the probes can make an additional, site-specific or probe-specific calibration. Typically, the site-specific or probe-specific calibration does not relate the actual moistness M of the soil (in our case, the volumetric moisture content θ_g obtained gravimetrically) directly to the electrical output of the sensor Q, but to an approximate moistness of the soil obtained from the universal calibration curve, $M_u(Q)$ (in our case, to the volumetric moisture content θ_u). The relation $M(M_u)$ (in our case, $\theta_g(\theta_u)$) is called a secondary calibration curve. A universal, site-specific or probe-specific composite calibration curve is then obtained as a superposition of the universal primary calibration curve, $M_u(Q)$, and the universal, site-specific or probe-specific secondary calibration curve $M(M_u)$, respectively:

$$M(Q) = M[M_u(Q)] \tag{1}$$

Most methodologies of secondary calibration are based on a two-point procedure, in which the probe outputs are measured for a particular soil at two known but considerably different moisture contents. Then, if there are no firm grounds why to do it differently, the secondary calibration curve is assumed to be a straight line

$$M = A + B\,M_u \tag{2}$$

where:

A and B – site-specific or probe-specific calibration constants

Often we have to content ourselves with a single-point procedure, resulting in a shift of the universal calibration curve by an offset value A. Then, instead of Eq. (2), the secondary calibration curve is:

$$M = AC + M_u \tag{3}$$

where:

AC – additive constant

A special laboratory facility or a dedicated field experiment is needed in order to arrive at a more comprehensive, non-linear secondary calibration curve. Both the site-specific and the probe-specific calibrations are based on the assumption that the effect of the soil (the "site") and effect of the probe can be regarded as systematic and removable by calibration. If, however, no site-specific and probe-specific calibration has been made, these effects must be taken as random and contributing to the overall variability of results, because, in this case, we actually insert randomly chosen probes into randomly chosen soils.

The variability of sensor readings, whatever its cause, can be expressed quantitatively either as the standard deviation of repeated measurements or as the maximum error (e.g., three standard deviations). The accuracy is defined in terms of deviations between the actual measurement results and the true moisture content of the soil, while under reproducibility (sometimes also referred to as precision) we understand the variability of repeated measurements, notwithstanding the true moisture content. The probe-to-probe variability is a specific type of reproducibility arising when a probe is replaced by another one. The term sensor is used to denote the actual sensing element of a soil moisture measuring equipment, while the expression "probe" is used for the sensor together with an accompanying electrical circuit which makes the input and output of the sensor technically manageable. In this sense, either of the two instruments we tested (Virrib and ThetaProbe) are probes rather than sensors, but it is often their sensing elements (the sensors) that are of our primary interest. We therefore use the words sensor and probe interchangeably.

The measurements described in this paper were undertaken in order to improve the accuracy of field measurements made for applied research purposes (see below). In addition to this immediate purpose, some conclusions of more general nature were made and are reported below. One-point field calibration was done first. As there were many parallel sensors involved, the procedure also possessed some features of a multiple-point calibration. It was then supplemented by a laboratory check. Reference is made below to a more detailed laboratory calibration of the same ThetaProbes and other dielectric sensors by Kučera *et al.* (2007).

METHODS AND MATERIALS

The sensors tested in this study were the AMET–consortium Virrib phase transmission probes (http://www.amet.cz/virriben.pdf, Muñoz-Carpena 2004) with sensing elements in the form of two concentric rings with diameters 200 and 280 mm, respectively, made of metallic rods 11 mm in diameter, and the Delta-T ThetaProbe ML2x amplitude-domain reflectometry probes (Delta-T 1999; Miller & Gaskin 2007) with sensing elements in the form of four parallel metallic rods 65 mm long and 3.3 mm in diameter. The Virrib probes have been widely used in the Czech Republic and previously in Czechoslovakia for automated and semi-automated irrigation control. The outputs of the probes (direct current in the case of Virribs, voltage in the case of ThetaProbes) were measured and recorded by EMS Modulog dataloggers (www.emsbrno.cz) or AMET hand-held meters. The excitation of the probes was standard. Up to twenty different Virrib sensors and up to twenty four ThetaProbes were tested in parralel.

Three-year field experiments, aimed at the exploration of potato (*Solanum tuberosum* L.) growing technologies on a European scale from the viewpoints of agronomic and economic efficiency, quality of tubers and nitrate leaching, were carried out over three growing seasons 2003–2005 within an international project FertOrgaNic (www.fertorganic.org). The experimental site, Valečov, lies at 49°38'40" N, 14°30'25" E and 461 m a.s.l. near Havlíčkův Brod town in the Bohemo-Moravian highland, Czech Republic. A more detailed description of the site and the design of experiments can be found, for example, in Plauborg (2006). Some information is also contained in the papers by Doležal *et al.* (2005) and Zumr *et al.* (2006). The soil type is deep Stagnosol (IUSS Working Group WRB 2007) on weathered paragneiss. The topsoil, about 25 to 30 cm thick, is quite fertile, due to a long history of previous intensive cultivation. The subsoil is acid, dense and less favourable to root growth. The soil is fairly heterogeneous due to heterogeneity of the parent rock. Typical soil properties are given in Tables 1 and 2. The

Table 1. Typical physical properties of the Valečov soil (area C); figures is brackets indicate standard deviations

Depth (cm)	Particle density (g/cm^3)	Dry bulk density (g/cm^3)	Porosity (% vol.)	Field capacity (% vol.)	Wilting point (% vol.)	Clay < 0.002 mm (% mass)	Silt 0.002–0.05 mm (% mass)	Sand 0.05–2.0 mm (% mass)
20	2.65 (0.03)	1.52 (0.05)	42.4 (1.8)	36.2 (1.2)	14.0 (0.4)	16.5 (1.7)	37.2 (2.6)	46.4 (1.3)
40	2.69 (0.02)	1.52 (0.08)	43.6 (3.2)	35.1 (3.1)	14.2 (1.4)	22.5 (2.8)	33.2 (5.0)	44.3 (6.5)
60	2.69 (0.01)	1.57 (0.06)	41.5 (2.3)	36.6 (3.2)	15.1 (3.1)	28.8 (7.8)	21.4 (7.3)	49.8 (15.1)
80	2.68 (0.03)	1.67 (0.09)	37.7 (3.2)	33.9 (3.4)	13.6 (4.2)	24.8 (8.7)	18.4 (10.3)	56.7 (18.6)
120	2.70 (0.04)	1.71 (0.03)	36.6 (1.4)	23.6 (6.2)	9.4 (2.8)	14.4 (7.1)	11.3 (5.9)	74.3 (12.7)

The field capacity was estimated using an empirical laboratory procedure known as the maximum capillary capacity (Klika *et al.* 1954); the wilting point was estimated from the soil texture using a local pedotransfer function (Váša 1960)

Table 2. Typical chemical properties of the Valečov soil (area C); figures is brackets indicate standard deviations

Depth (cm)	Oxidisable carbon (% mass)	Cation exchange capacity (cmol(c)/kg dry soil)	CEC base saturation (%)	pH (H_2O)
20	1.25 (0.04)	13.1 (0.7)	91.0 (4.4)	7.0 (0.0)
40	0.32 (0.07)	9.1 (1.9)	74.3 (9.1)	6.9 (0.0)
60	0.15 (0.06)	10.8 (2.9)	75.3 (12.3)	6.5 (0.4)
80	0.12 (0.08)	10.4 (3.9)	77.0 (13.9)	5.9 (0.6)
120	0.07 (0.05)	8.4 (5.3)	68.3 (9.1)	5.3 (0.1)

soil does not contain any free carbonates. The electrical conductivity of soil solution varies between 40 and 80 mS/m. The movement of water in this soil after rain, snowmelt or irrigation is distinctly preferential, occurring via macropores of various types, which contributes to soil moisture heterogeneity. The potato plants were grown in elevated ridges. Drip irrigation lines were placed on the top of ridges and covered with a layer of soil about 3 to 8 cm thick. The spacing between the potato ridges, between plants in the ridges and between drippers in drip lines were, respectively, 0.75 m, 0.35 m and 0.30 m. The level of the tops of the ridges was approximately 20 cm higher than the level of the bottoms of the furrows between them. Groundwater table was absent, except for short periods of waterlogging (lasting between few hours and few days) after intensive snowmelt or rain events.

As the experimental plots had to be moved each year to a new place in accordance with the crop rotation plan, all sensors had to be re-installed each year in spring after the planting of potato and removed in autumn before the harvest. All sensors were placed beneath the potato ridges and in the middle between two neighbouring potato plants (the latter rule was not always observed with Virribs). In drip-irrigated treatments, no regard was paid to the relative position of sensors with respect to the nearest drippers, as the drip lines were, by the time of sensor installation, already covered with soil and, therefore, invisible. Everywhere in this paper, the depth of a sensor below soil surface is expressed as the vertical distance between the geometrical centre of a sensing assembly and the average soil surface. The latter is defined as the level lying in the middle between the tops of ridges and the bottoms of furrows. The depths defined in this manner are by about 10 cm smaller than the depths taken with respect to the tops of ridges. The numbering of sensors before 2005 was only temporary and was not recollected after the removal of sensors from the field. Hence, the results of 2003 and 2004 cannot be related to each other and to the results of 2005 in terms of individual sensors, but only in terms of the whole sets of sensors.

The Virrib probes were installed horizontally into pre-made pits about 40 cm in diameter. The depth of each pit was by about 5 to 10 cm larger than the nominal depth of sensor installation, which was either 30 or 60 cm beneath the average soil surface. The bottom of the pit was covered with about 5 to 10 cm of disturbed soil, previously excavated from the pit from approximately the same depth. A Virrib probe was then laid onto this earthen pillow and covered with another layer of the same soil, about 10 to 15 cm thick. The soil layer so made and containing the sensor was then compacted by trampling in order to approximately simulate the bulk density of the original undisturbed soil. A 100 cm^3 core sample was then taken from this compacted layer from the middle of the inner ring of the sensor. The empty hole so created was refilled with the same soil and similarly compacted. Then further layers of disturbed soil were added on the top of the layer already compacted. Each new layer, up to the soil surface, was also compacted by trampling or pressing by hand. Each such layer was made as exactly as possible from the soil that had been previously excavated from about the same depth, and some care was taken to make the bulk density of the re-compacted soil approximately the same as that of the original undisturbed soil (but this was not tested by any exact means). The topsoil above the Virrib sensors was then re-formed into ridges and furrows. The potato plants, if they had to be removed before the probe installation, were re-planted. Readings of freshly installed probes were then taken manually and, in most cases, repeatedly within few hours or days after the installation. In 2004, readings of some probes had to be reconstituted by extrapolation from the datalogger records made few days later. In 2005, additional readings were taken when the installation pits were only half-refilled, i.e., when the thickness of the recompacted soil layer above the sensor was only about 15 cm, fairly smaller than the final thickness.

The ThetaProbes were installed in 2004 and 2005 in the topsoil only, without using access tubes. The depths of installation were 0 and 20 cm beneath the average soil surface. Shallow installation pits were made in the soil with a hand shovel. The needles of each ThetaProbe were then pushed horizontally into the vertical wall of a particular pit so made at the appropriate depth. In 2005, a reading of each ThetaProbe was taken manually shortly after the first installation. Then the ThetaProbe was removed, a disturbed soil sample was taken exactly from the place where there had been the needles of the ThetaProbe and an undisturbed 100 cm^3 core was taken from the vicinity of that place from the same depth. Then the installation pit was broadened, a new undisturbed vertical wall was exposed, the ThetaProbe was re-installed as above and its manual reading was taken again. Then, both in 2004 and in 2005, the installation pit was refilled with the soil previously excavated. The refill was compacted gently by hand. In 2004, one undisturbed 100 cm^3 core was taken in the vicinity of each ThetaProbe about two weeks after installation and the corresponding readings of the probes were extracted from the EMS datalogger records. The cores in 2004 were taken at depths and positions analogous to those where the needles of individual ThetaProbes were placed but at some distance from them (of the order of one or several meters).

In spring 2005, all sensors were checked in the laboratory prior to their installation in the field. The soil used for this purpose was a commercially available topsoil of loamy sand texture, similar to the Valečov topsoil (see the first line of Tables 1 and 2) but with a somewhat higher content of organic carbon and sand. No detailed textural or chemical analyses of this material have been made. The laboratory experiments were carried out at usual laboratory temperatures between 20 and 24°C. The tap water used for moistening the soil had electrical conductivity about 30 mS/m.

The procedure used for checking Virribs resembled a true laboratory calibration. Dry soil was passed through a 2 mm sieve and put into a large plastic dish. The internal diameter of the dish was about 52 cm at the bottom and about 60 cm at the top. The total depth of the dish was about 34 cm. The average thickness of the soil layer in the dish varied between 8 and 15 cm. One Virrib sensor after another were placed into this soil so that the sensor was surrounded by the soil from all sides. Then a manual reading of the sensor was taken and the sensor was removed. When all sensors had undergone this procedure, some

Table 3. The appearance and properties of the soil at individual moisture steps of the laboratory check in 2005

Step	Appearance	Dry bulk density ρ_b mean (SD) (g/cm^3)	Moisture content θ_g mean (SD) (m^3/m^3)
1	dry, freely flowing floury powder	1.270 (0.018 257)	0.052 (0.001 927)
2	still quite dry and flowing	1.260 (0.008 165)	0.054 (0.000 926)
3	still relatively dry, few small crumbs	1.230 (0.014 142)	0.068 (0.002 901)
4	the same as 3	1.172 (0.017 889)	0.085 (0.001 920)
5	small crumbs, soft, light colour	1.108 (0.013 038)	0.101 (0.010 372)
6	the same like 5 but dark colour	1.138 (0.031 145)	0.122 (0.007 229)
7	larger and tougher crumbs, to be pressed a little by hand	1.218 (0.027 749)	0.158 (0.003 894)
8	sticky tough crumbs, to be pressed	1.370 (0.035 355)	0. 218 (0.004 920)
9	tough plastic mass, to be pressed	1.712 (0.016 432)	0.313 (0.005 206)
10	soft plastic mass, easy to press	1.684 (0.015 166)	0.334 (0.005 608)
11	soft sticky mass near the liquid limit	1.618 (0.010 954)	0.352 (0.004 409)

SD – standard deviation

amount of water was added to the soil, using a laboratory rinsing bottle, and the soil in the dish was thoroughly mixed and homogenized by hand. Then again all Virribs, one after another, were inserted into this soil and their readings were taken. Altogether eleven different moisture states of the soil (referred to below as moisture steps) were prepared, from the air-dry soil at the start to a very soft plastic-consistence soil in the end. Four to five undisturbed 100 cm^3 core samples were taken from the soil in the dish during each moisture step to determine its moisture content and bulk density gravimetrically. Table 3 describes the appearance of the soil, its dry bulk density and its moisture content, including their standard deviations, at each moisture step. The data of Table 3 show that the homogeneity of mixing was quite good. The soil was not compacted by any means, except that at the moisture step 7 and at the following steps it had to be compressed a little by hand in order to come into a more intimate contact with the sensor rods. At the last (11^{th}) moisture step, the reading of each probe was taken three times: once with a thin layer of soil (about 2 cm) both beneath and above the sensor, for the second time with soil layers of medium thickness (about 4 cm, corresponding to what was done at previous moisture steps) and, for the third time, with the layers about 6 cm thick on both sides (to achieve this, the horizontal diameter of the soil cake had to be somewhat reduced). Four Virribs only were tested at first three moisture steps, but all twenty sensors were tested at the remaining eight steps. At each moisture step, three of the sensors were used to test the repeatability of the insertion (inserting the sensor into the soil, taking the reading and removing the sensor) by doing it three times.

This procedure was chosen because of its speed and because we assumed *à priori* that the effect of variable bulk density and of the limited soil volume around the sensor would be small. Other techniques for manipulating the soil moisture content would be more time-consuming. As a matter of fact, the dry bulk density of the soil established differently at each moisture step. At the start of the experiment it was at a medium level. Then, when moderately moistened, the soil created small soft crumbs of millimetre size with similarly small air gaps between them. The resulting dry bulk densities of this soil were very low. Later, at higher moisture contents, the dry bulk density increased considerably, only to diminish a little at the last two moisture steps. During the procedure, the surface of the soil in the dish either rose or sank, corresponding to the changes in its dry bulk density. The total height of the sand mass in the dish was not measured exactly. The total amount of the dry soil matter in the dish gradually diminished due to repeated sampling. By the end of the procedure, there was not enough soil remaining in the dish to make a continuous layer covering the whole bottom of the dish. The diameter of the soil cake was then slightly smaller than the diameter of the dish, but the cake still surrounded the Virrib sensor from all sides.

The ThetaProbes were tested in the laboratory only once, after the last (11^{th}) moisture step of testing Virrib sensors. The procedure described below was repeated twice, with twelve sensors in either round, so that altogether twenty four sensors were tested. The needles of all twelve sensors were pushed vertically side by side into the cake of the moist soil in the dish. The readings of the sensors were taken, the sensors were then removed and disturbed soil samples for gravimetric soil moisture determination were taken exactly from the spots in which the sensors needles had been placed, one sample for each sensor. One undisturbed 100 cm^3 core sample was also taken in each round.

The primary universal calibration curve (actually a straight line) for Virribs was:

$$\theta_u = 0.1 \times I \tag{4}$$

where:

θ_u – output of the universal calibration curve in terms of the volumetric soil moisture content (m^3/m^3)

I – sensor output current in milliampères

The primary universal calibration curve used for ThetaProbes was:

$$\theta_u = A + BV + CV^2 \tag{5}$$

where:

θ_u – the same as above

V – output voltage of the probe (mV)

$A = 0.0457839$, $B = 0.0001219$, $C = 3.00 \times 10^{-7}$ – empirical constants

The Eq. (5) was obtained by quadratic approximation of the Delta-T (1999) linearization table for mineral soils. Because of different numerical techniques used, Eq. (5) slightly differs from (but is still in a reasonable agreement with) both the linear and the third-order polynomial equations with which the ThetaProbe outputs for a range of solvents of different permittivities were approximated (Delta-T 1999; Miller & Gaskin 2007).

The standard deviation of repeated measurements was used in this paper as a universal measure of reproducibility. To facilitate optical comparison of various standard deviations, differing from each other by several orders of magnitude, their values are presented in the tables as fixed-point numbers with six decimal places. This of course does not imply any information about their precision. The standard deviations obtained separately from several parallel subsets of data were averaged over all such subsets. Because of the complexity of the problem, the non-linearity of the effects (such as those depicted in Figures 2, 4 and 6) and the scarcity of measurements, we did not try to apply a regular analysis of variance. For the sake of data homogeneity, all statistical calculations were made with the data expressed as volumetric moisture contents (in m^3/m^3), i.e., prior to these calculations the electrical outputs of the probes had been were transformed into m^3/m^3 using the universal primary calibration curves.

The probability of exceedance of the additive constants was estimated using the Hazen plotting position equation (Hazen 1930; Cunnane 1989):

$$P_e = (m - 0.5)/n \quad (6)$$

where:

P_e – estimated probability of exceedance

m – rank in descending order

n – total number of cases

Significance of correlation coefficients was tested using the t-statistic (Maidment 1993, p. 17.30):

$$t = |R| \frac{\sqrt{n-2}}{\sqrt{1-R^2}} \quad (7)$$

where:

R – correlation coefficient

n – number of observations

The correlation was considered significant if the t-statistic according to Eq. (2) was larger than the doubled-sided t_{crit} (the Student distribution quantile) for the same degrees of freedom and the significance level P (the probability of unwarranted rejection of the null hypothesis).

RESULTS AND DISCUSSION

Virribs

In each year, the volumetric moisture content θ_u obtained from a particular sensor's reading via the primary calibration line (Eq. (4)) was compared with the volumetric moisture content θ_g obtained gravimetrically. The resulting graphs for the field calibration 2003 and the laboratory check 2005 are shown in Figures 1 and 2, respectively. Note that

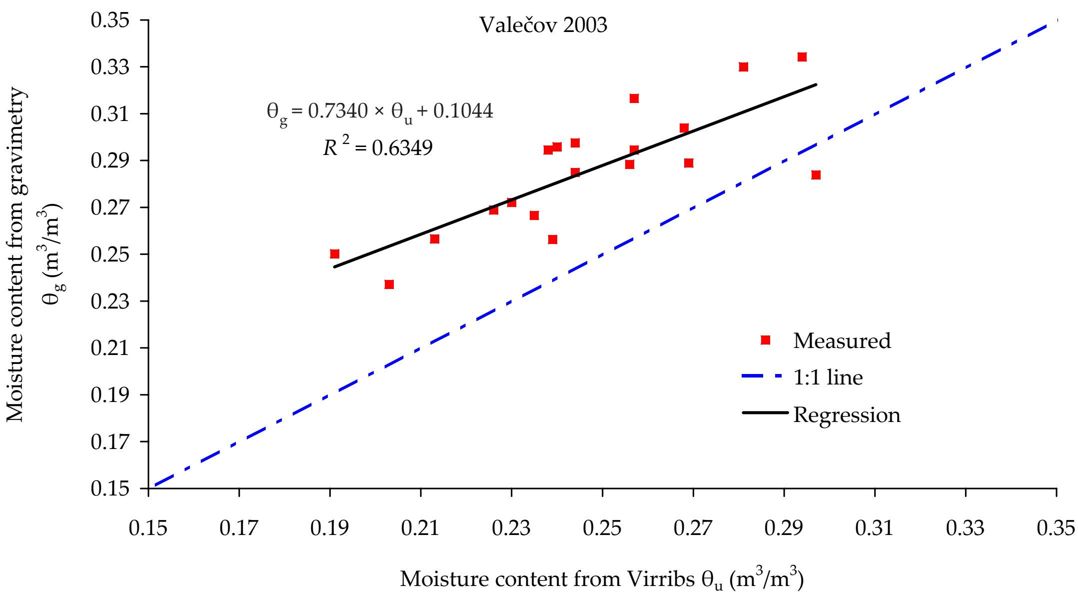

Figure 1. Soil moisture content θ_g obtained gravimetrically vs. soil moisture content θ_u obtained from Virrib reading via the primary calibration line (Eq. (4)); field calibration, Valečov, 2003

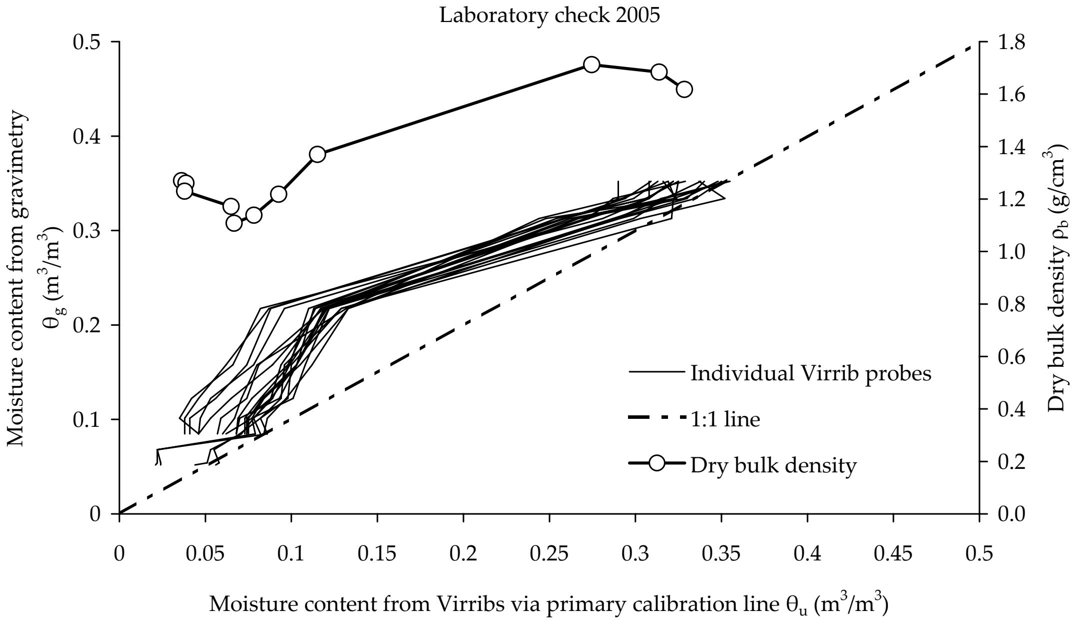

Figure 2. Soil moisture content θ_g obtained gravimetrically (averaged over 4 to 5 parallel cores) vs. soil moisture contents θ_u obtained from individual Virrib probes via the primary calibration line (Eq. (4)), for individual moisture steps; the average dry bulk density ρ_b of the soil at individual moisture steps is also plotted as a function of the moisture content from Virribs, θ_u, averaged over all probes; laboratory check, humous loamy-sand, 2005

the moisture content obtained gravimetrically is plotted on the vertical axis, in accordance with our definition of the secondary calibration curve. The field calibration graphs for 2004 and 2005 (not shown) look similar, except that the regression and correlation coefficients vary from year to year. The statistics are shown in Table 4, where P is the probability of unwarranted rejection of the no-correlation hypothesis.

The slopes of the regression lines obtained in 2003 (Figure 1) and 2004 (not shown) are not much different from unity. This fact suggests that perhaps the use of unit slope for the secondary calibration line would be acceptable. No linear regression was calculated for the 2005 laboratory check, because the dependence of θ_g on θ_u was non-linear (see Figure 2). However, even in Figure 2 we see that for the higher moisture content range, most often encountered in the field, the secondary calibration curve may be approximated by a straight line. The fact that the slope of this straight line is smaller than unity can be, at least partially, explained by lower dry bulk densities at lower moisture contents.

The difference between the soil moisture content obtained gravimetrically, θ_g, and that obtained from a Virrib sensor via the primary calibration curve, θ_u, is further referred to as the additive constant AC (and not as an "offset", to make apparent that it cannot always be used as an offset to correct the measurements):

$$AC = \theta_g - \theta_u \quad (8)$$

AC represents the number that must be added to a Virrib reading θ_u (m^3/m^3) transformed via the primary calibration curve in order to obtain an unbiased estimate of the true soil moisture content for a particular sensor, soil, and soil mois-

Table 4. Linear regression and correlation between the moisture content from gravimetry (θ_g) and that from Virribs via the primary calibration line (θ_u), for the field calibrations

Year	Regression equation	Observations n	Correlation coefficient R	Significance
2003	$\theta_g = 0.7340\ \theta_u + 0.1044$	19	0.7968	highly significant ($P < 0.001$)
2004	$\theta_g = 0.8268\ \theta_u + 0.1025$	20	0.6431	highly significant ($P < 0.005$)
2005	$\theta_g = 0.3288\ \theta_u + 0.2115$	20	0.3401	insignificant ($P > 0.1$)

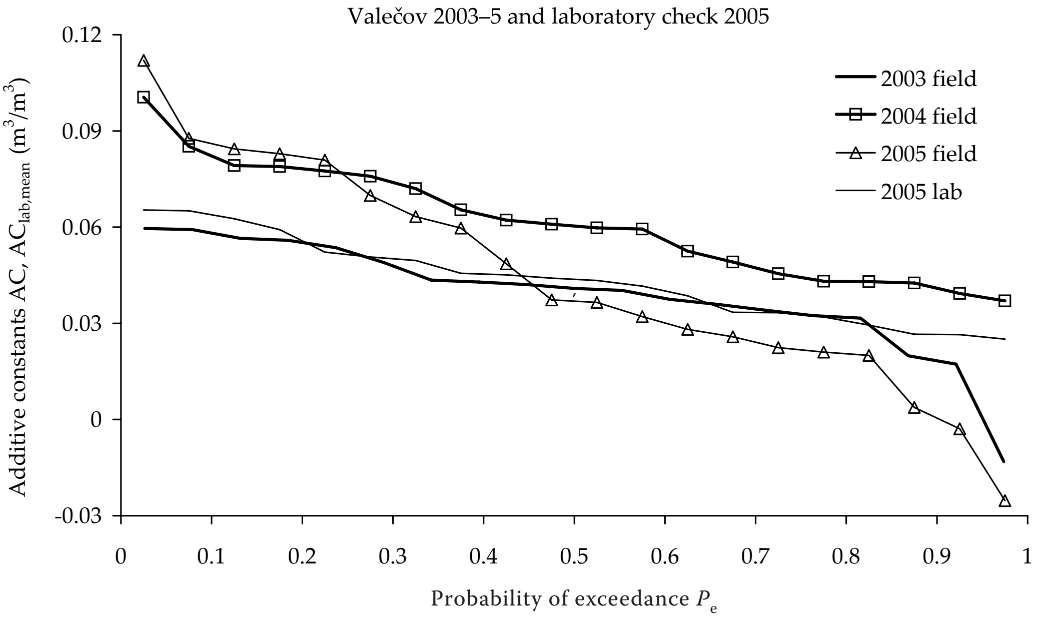

Figure 3. Probability-of-exceedance curves of additive constants *AC* according to Eq. (8) for individual Virrib sensors in different years; each "field" curve $AC(P_e)$ represents a particular situation at the time of probe installation; the "2005 lab" curve $AC_{lab,mean}(P_e)$ represents the average additive constants over the moisture steps 4 to 11

ture status. We assume on this occasion that the gravimetric determination of soil moisture content itself is unbiased. As the numbering of individual sensors was different in different years and the equivalence between particular years' numbers of the same sensors is mostly unknown, we cannot compare the behaviour of particular sensors in different years. However, we can compare the behaviour of the whole sets of sensors. The sets of additive constants *AC* obtained in particular years were therefore sorted in a descending order and the additive constants were plotted against their probability of exceedance. The results are presented in Figure 3, together with a similar curve for the mean additive constants $AC_{lab,mean}$ obtained during the 2005 laboratory check, averaged over the moisture steps 4 to 11 (at which all twenty Virribs were tested). The probability-of-exceedance curve for the 2005 laboratory check describes in the best way the variability among probes generated by the process of their manufacturing. This conclusion is corroborated by the fact that the central parts of all four probability-of-exceedance curves have similar slopes. However, the four curves in Figure 3 are shifted with respect to each other and there are also other large differences among them, especially near both ends of the curves. These differences are to be mainly attributed to the difficulty of reproducing the same bulk density of the refill soil around the Virrib probe when the latter is being re-installed.

The dependence of additive constants of individual sensors AC_{lab}, as obtained at particular moisture steps during the 2005 laboratory check, on the average soil moisture content at particular moisture steps is plotted in Figure 4. This non-monotonous dependence can be best explained by the variation of the dry bulk density of the soil (also plotted in Figure 4). As we do not know the soil moisture content in advance (and also because the Virrib sensors were not surrounded by enough soil during the laboratory check), we cannot use these additive constants as offsets for correcting the Virrib measurements. The average additive constants $AC_{lab,mean}$ of individual sensors during the laboratory check of 2005, averaged over the moisture steps 4 to 11, are compared in Figure 5 with the additive constants *AC* of the same sensors obtained during the field calibration in the same year. The two sets of additive constants are virtually uncorrelated ($P > 0.2$). The field additive constants reflect mainly the differences among the ways of installation of individual sensors, rather than the differences among the sensors themselves (which, in turn, are mainly reflected by the differences in average laboratory additive constants). The addi-

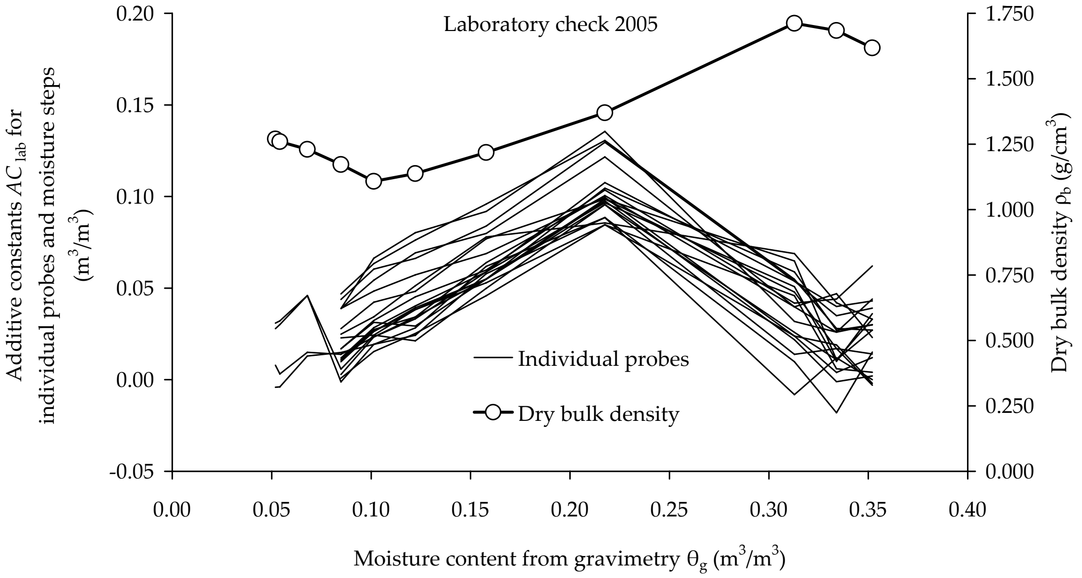

Figure 4. Additive constants *AC* according to Eq. (8) for individual Virrib probes and individual moisture steps; the moisture steps are characterized by the soil moisture content θ_g obtained gravimetrically (averaged over 4 to 5 parallel cores); the average dry bulk density ρ_b of the soil at individual moisture steps is also plotted; laboratory check, humous loamy-sand, 2005

tive constants from the field calibrations are loosely but often significantly and positively correlated to the soil moisture contents obtained gravimetrically (Table 5). At the same time, they are negatively but virtually insignificantly correlated to the dry bulk density (Table 6). Therefore, at least for the soils and the depths of installation similar to those in Valečov, the effect of the dry bulk density of the soil on the Virrib field readings is small.

The average response of Virribs during the laboratory check can be approximated by a cubic secondary calibration equation (Figure 6). However, the size of the zone of influence of Virribs, especially in the direction perpendicular to the sensing rings, is quite large, and requires that the sensor be covered with a sufficient layer of soil. This condition was not fulfilled during our laboratory check, which is illustrated by Figure 7. This figure displays the readings of individual Virribs when they were surrounded by a soil layer of specified thickness both from the bottom and from above (thin = about 2 cm, medium = about

Table 5. Linear regression and correlation between the additive constants (*AC*) for Virribs and the moisture content from gravimetry (θ_g) during the field calibrations

Year	Regression equation	Observations *n*	Correlation coefficient *R*	Significance
2003	$AC = 0.0013\ \theta_g + 0.0004$	19	0.2015	insignificant ($P > 0.2$)
2004	$AC = 0.4995\ \theta_g - 0.0877$	20	0.6423	highly significant ($P < 0.005$)
2005	$AC = 0.6480\ \theta_g - 0.1457$	20	0.5543	significant ($P < 0.05$)

Table 6. Linear regression and correlation between the additive constants (*AC*) for Virribs and the dry bulk density from gravimetry (ρ_b) during the field calibrations

Year	Regression equation	Observations *n*	Correlation coefficient *R*	Significance
2003	$AC = -0.0205\ \rho_b + 0.0714$	19	0.0985	insignificant ($P > 0.2$)
2004	$AC = -0.0742\ \rho_b + 0.1729$	20	0.1806	insignificant ($P > 0.2$)
2005	$AC = -8.1025\ \rho_b + 0.1764$	20	0.1591	insignificant ($P > 0.2$)

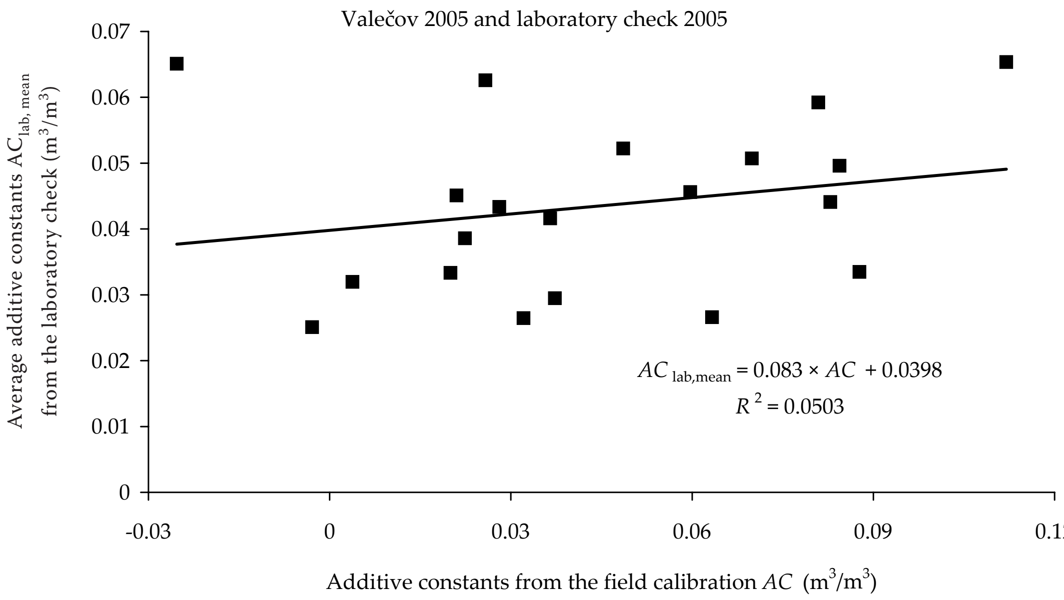

Figure 5. Comparison of average additive constants $AC_{lab,mean}$ obtained for individual Virrib probes during the moisture steps 4 to 11 of the laboratory check in 2005 and the additive constants AC obtained for the same probes during the one-point field calibration in 2005

4 cm, thick = about 6 cm of soil on either side). To make the graph more lucid, the probes on the horizontal axis of Figure 7 are ordered so that the medium-layer readings descend from left to right. Evidently, the zone of influence of Virrib sensors reaches farther than 6 cm on both sides. The difference between the thick and the medium series in Figure 7 might have been even larger, if it were not for the smaller diameter of the soil cake in the thick configuration. A similar conclusion

Table 7. Standard deviations (SD) (m^3/m^3) signifying typical errors of soil moisture measurements with Virrib sensors due to various factors

Way of calculation	SD	Dominant factors involved
SD of additive constants, field 2003	0.017 435	the way of placement of the probes in the field, manufacturing of individual probes
SD of additive constants, field 2004	0.017 648	
SD of additive constants, field 2005	0.035 067	
SD of core samples, field 2003, 30 cm	0.022 137	heterogeneity of the soil and of its moisture content in the field
SD of core samples, field 2004, 30 cm	0.026 769	
SD of core samples, field 2005, 30 cm	0.035 401	
SD of core samples, field 2003, 60 cm	0.026 834	
SD of core samples, field 2004, 60 cm	0.018 977	
SD of core samples, field 2005, 60 cm	0.024 485	
SD among probes, averaged over all moisture steps, laboratory check 2005	0.016 896	manufacturing of individual probes, their way of placement in the laboratory and soil heterogeneity
SD among parallel cores, averaged over all moisture steps, laboratory check 2005	0.004 483	heterogeneity of the soil and of its moisture content in the laboratory
SD of readings after repeated placement, averaged over all moisture steps and probes tested, laboratory check 2005	0.005 266	the way of placement of the probe in the laboratory soil
SD of readings taken over six hours, few days after installation, field 2004	0.000 296	the electrical stability of the Virrib sensor – EMS datalogger assembly and the temporal soil moisture variation

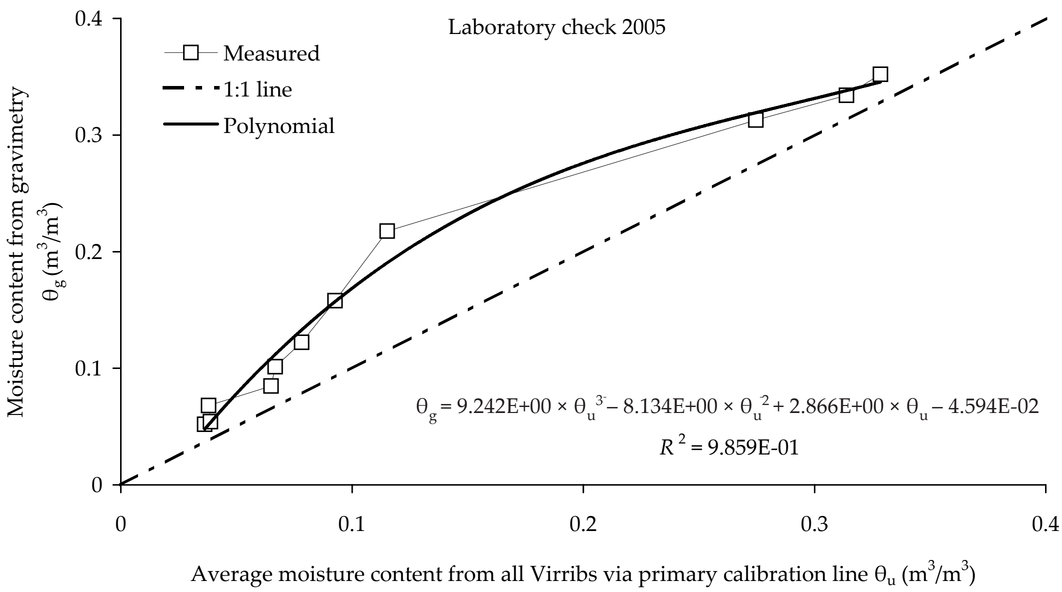

Figure 6. Average secondary calibration curve for Virribs, derived from the laboratory check in 2005. Each point represents a single moisture step

also follows from the field measurement made in 2005, when the calibration readings were taken twice: once with a Virrib probe covered with a recompacted soil layer only about 15 cm thick (reading X), and for the second time with the probe completely covered up to the soil surface (reading Y). Comparison of the two sets of readings shows that there is a systematic difference between the two (the averages of X and Y, in terms of the volumetric moisture content obtained via the primary calibration line, being 0.2374 m^3/m^3 and 0.2503 m^3/m^3, respectively) and this difference is statistically significant (tested by a double-sided t-test for $P = 0.05$). Hence, even a 15-centimetre soil cover need not be enough. To be on the safe side, we suggest that the covering layer over Virrib sensors, if these are placed horizontally, should be at least 30 cm. The cubic secondary calibration curve proposed in Figure 6 should not be therefore used for correcting field measurements. Instead, it seems more accurate to assume for this purpose a secondary calibration straight line with a unit slope and with an offset determined each year anew for each probe.

Finally, our data allow us to estimate, albeit incompletely, the variability of Virrib readings due to various sources of error. The magnitude of the variability is expressed as a standard deviation or an arithmetic mean of the relevant standard deviations. The results are summarized in Table 7 and are, of course, only valid for the conditions similar to those encountered in the Valečov loamy soil or the laboratory loamy sand used. The standard deviations in last three lines in Table 7 are relatively low and indicate that Virribs can be used for practical purposes, if different offsets of different Virrib probes are taken into account.

ThetaProbes

In both 2004 and 2005, the volumetric moisture content θ_u obtained during the field calibration of a particular sensor via the universal primary calibration curve (Eq. (5)) was compared with the volumetric moisture content θ_g obtained gravimetrically. The results are shown in Figures 8 and 9. The measured points are grouped into two distinct clusters, one for the average depth 0 cm (for lower moisture contents and lower dry bulk densities) and the other one for the average depth 20 cm (for higher moisture contents and higher dry bulk densities). The regression lines in Figures 8 and 9 depart from the 1:1 line, and this is mainly because of the bulk density variability. In the qualitative sense, this conclusion is corroborated by the results of laboratory calibration, made with the same set of ThetaProbes in 2006 in fine quartz sand (Kučera *et al.* 2007). Their secondary calibration curve is also plotted in Figures 8 and 9. Its upward curvature is generated by the

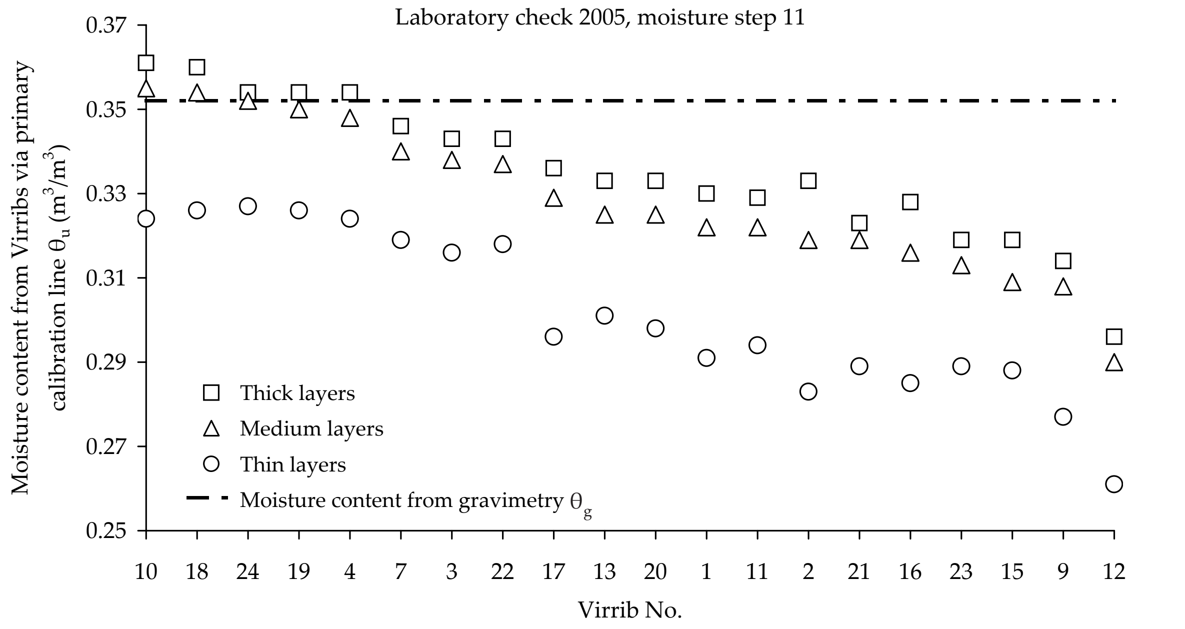

Figure 7. Comparison of Virrib readings θ_u obtained during the laboratory check in 2005 at the moisture step 11, when the sensing rings were surrounded by soil layers of different thickness (thin = about 2 cm on either side, medium = about 4 cm on either side, thick = about 6 cm on either side); the average moisture content θ_g obtained gravimetrically at the same moisture step is also indicated

lower dry bulk density of the sand in the middle of the moisture content range. Quantitatively, however, the secondary field calibration lines of 2004 and 2005 (the regression lines in Figures 8 and 9) are different from the secondary laboratory calibration curve of Kučera *et al.* (2007), because the fine quartz sand used by Kučera *et al.* is considerably different from the loamy and

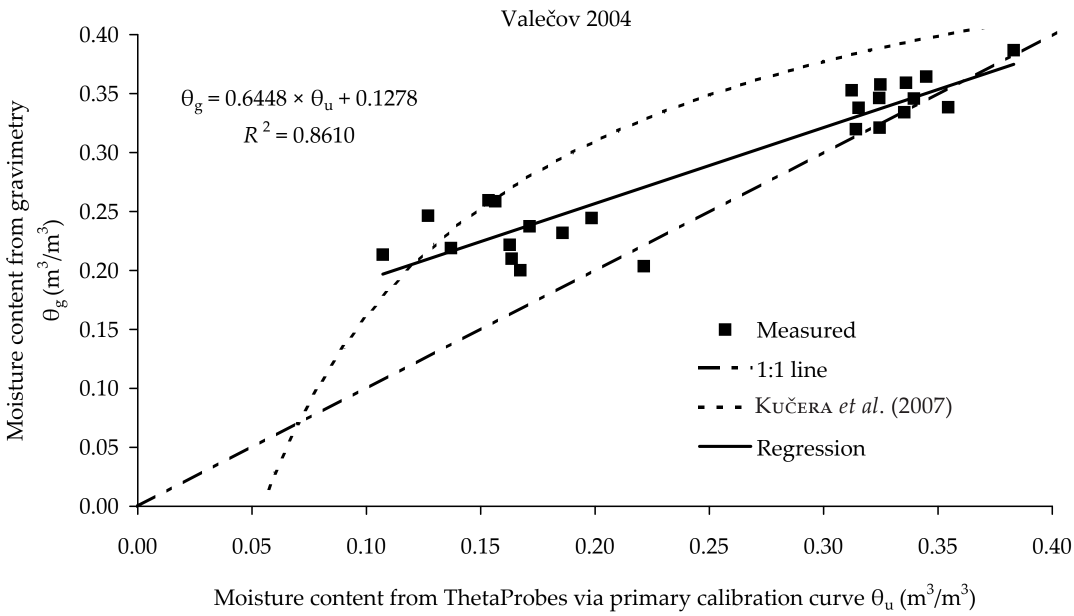

Figure 8. Soil moisture content θ_g obtained gravimetrically vs. soil moisture content θ_u obtained from the readings of ThetaProbes via the primary calibration curve (Eq. (5)); field calibration, Valečov, 2004; the secondary calibration line obtained by Kučera *et al.* (2007) for quartz sand is also shown for comparison

humous Valečov soil used by ourselves. For each particular ThetaProbe and a particular year, an additive constant *AC* according to Eq. (8) can be derived from the field calibration. The details are not shown. These additive constants are quite large, because the measured points in Figures 8 and 9 deviate considerably from the 1:1 line. Better results can be obtained when the ThetaProbe readings are transformed via the secondary calibration lines (which are the regression lines in Figures 8 and 9) and the (residual) additive constants are then calculated by subtracting the moisture contents determined gravimetrically from the moisture contents obtained as outputs of these secondary calibration lines. No details are shown here but the conclusion is illustrated by the corresponding standard deviations in Table 8 below, namely, the standard deviations of additive constants for the field 2004 and 2005, before and after applying the regression.

The laboratory check made in 2005, a sort of one-point calibration in a loamy-sand humous soil, resulted in a set of relatively small additive constants, AC_{lab}, for individual ThetaProbes. Among them, the minimum value was –0.00848 m^3/m^3, the maximum was 0.01374 m^3/m^3 and their standard deviation was 0.00598 m^3/m^3. When the additive constants AC_{lab} are added as offsets to the readings of ThetaProbes obtained during the 2005 field calibration and transformed via the primary calibration curve (5), the regression between the gravimetry (θ_g) and ThetaProbes ($\theta_u + AC_{lab}$) slightly improves in comparison with that displayed in Figure 9. Namely, one receives a regression equation $\theta_g = 0.6134\ (\theta_u + AC_{lab}) + 0.138$ instead of $\theta_g = 0.5962\ \theta_u + 0.1421$ and the determination coefficient becomes $R^2 = 0.9152$ instead of 0.904. The improved 2005 field calibration regression coefficient (0.6134) becomes in this way more similar to that obtained in 2004 (0.6448). The numbering of individual ThetaProbes was different in different years and no equivalence between the same sensor's numbers in 2004 and 2005 could be re-established. We can therefore only compare the global secondary calibration equations for 2004 and 2005, but not the perform-

Table 8. Standard deviations (SD) (m^3/m^3) signifying typical errors of soil moisture measurements with ThetaProbe sensors due to various factors

Way of calculation	SD	Dominant factors involved
SD of additive constants, laboratory 2005	0.005 983	manufacturing of individual probes and their way of placement in the laboratory
SD of additive constants, field 2004, before applying regression	0.040 097	soil heterogeneity, variable bulk density and inadequacy of the primary calibration curve
SD of additive constants, field 2004, after applying regression	0.023 629	mainly soil heterogeneity and variable bulk density
SD of additive constants, field 2005, before applying regression	0.036 513	soil heterogeneity, variable bulk density and inadequacy of the primary calibration curve
SD of additive constants, field 2005, after applying regression	0.014 874	mainly soil heterogeneity and variable bulk density
SD of core samples, field 2004, 0 cm	0.020 603	heterogeneity of the soil and of its moisture content in the field
SD of core samples, field 2005, 0 cm	0.018 853	
SD of core samples, field 2004, 20 cm	0.018 775	
SD of core samples, field 2005, 20 cm	0.028 200	
SD among probes, laboratory check 2005	0.005 235	manufacturing of individual probes, their way of placement in the laboratory and soil heterogeneity
SD among parallel gravimetric samples, laboratory check 2005	0.003 784	heterogeneity of the soil and of its moisture content in the laboratory
SD of readings taken over nine hours, few days after installation, field 2004, averaged over all probes	0.002 326	the electrical stability of the ThetaProbe sensor – EMS datalogger assembly and the temporal soil moisture variation

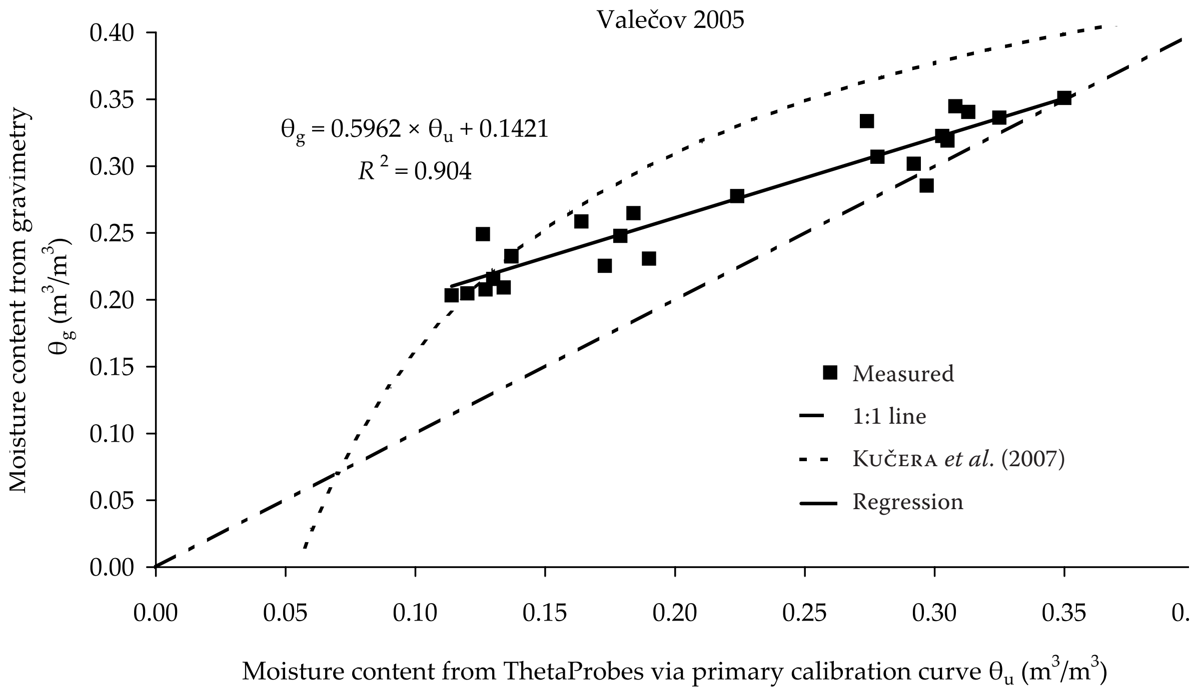

Figure 9. The same as Figure 8 for the field calibration, Valečov 2005

ance of particular sensors. Neither can we apply the offsets from the 2005 laboratory check to the field calibration data of 2004.

Table 8 gives an overview of particular standard deviation or averages of relevant standard deviations characterizing the effects of certain factors upon the variability of ThetaProbe measurements, when the soil is similar to the Valečov loamy topsoil or the loamy-sand topsoil used in the 2005 laboratory check.

Small standard deviation of the additive constants of ThetaProbes obtained during the 2005 laboratory check in a reasonably homogenous soil suggest that the large additive constants obtained in the field (see above) are due to the field soil bulk density and moisture content heterogeneity (and perhaps, an imperfect installation) and not due to the variability of properties of individual ThetaProbes. The standard deviation due to repeated insertions of the same probe into the same place was not tested, but Kučera *et al.* (2007) indicate that for fine quartz sand this is about 0.005 m^3/m^3.

CONCLUSIONS

What has been done is a sort of case study rather than a systematic research. The conclusions are therefore preliminary, and the results obtained arouse further questions and suggest further measurements. Nevertheless, the results show that the use of Virrib and ThetaProbe soil moisture sensors for applied research purposes is possible and recommendable. The probes cannot be used as they are but preliminary checks must be made, similar to those described above.

It is recommended, for conditions similar to those encountered in Valečov, that the Virrib readings be evaluated using a secondary calibration straight line with a unit slope and an offset determined each year anew for each probe by a one-point calibration during the probe installation. In addition, however, one must take into account that the installation procedure of Virrib sensors involves major disturbance to the soil of which the moisture is going to be measured, thus altering the physical properties of the soil.

The ThetaProbes, when installed in a topsoil similar to that in Valečov, should be also one-point calibrated but perhaps not necessarily every year. The secondary calibration curve can be a straight line with the slope smaller than unity, provided that an approximately single-valued and next-to-linear relation exists between the dry bulk density and the depth below the soil surface. The ThetaProbes themselves are more accurate than Virribs and their installation does not cause a large disturbance of the soil, but their sensitivity to the dry bulk density changes must be kept in mind.

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