01 Dec 2016

Ground-Penetrating Radar Water Content Mapping of Golf Course Green Sand Layers

Barry J. Allred

Robert S. Freeland

Katherine R. Grote
Missouri University of Science and Technology, grotekr@mst.edu

Edward L. McCoy

et. al. For a complete list of authors, see https://scholarsmine.mst.edu/geosci_geo_peteng_facwork/601

Recommended Citation

B. J. Allred et al., "Ground-Penetrating Radar Water Content Mapping of Golf Course Green Sand Layers," *Journal of Environmental and Engineering Geophysics*, vol. 21, no. 4, pp. 215-229, Society of Exploration Geophysicists, Dec 2016.
The definitive version is available at https://doi.org/10.2113/JEEG21.4.215

Ground-Penetrating Radar Water Content Mapping of Golf Course Green Sand Layers

Barry Allred[1], Robert Freeland[2], Katherine Grote[3], Edward McCoy[4], Luis Martinez[1] and Debra Gamble[1]
[1]USDA - Agricultural Research Service - Soil Drainage Research Unit, 590 Woody Hayes Drive, Columbus, OH 43210
[2]Biosystems Engineering and Soil Science Department, University of Tennessee, 2506 E. J. Chapman Drive, Knoxville, TN 37996
[3]Geosciences and Geological and Petroleum Engineering Department, Missouri University of Science and Technology, 1400 North Bishop, Rolla MO 65409
[4]School of Environment and Natural Resources, The Ohio State University, 2021 Coffey Road, Columbus, OH 43210
Corresponding Author Email: Barry.Allred@ars.usda.gov

ABSTRACT

Information on the spatial distribution of water content across the sand layer component of a golf course green can be important to golf course superintendents for evaluating drainage effectiveness and scheduling irrigation. To estimate the bulk volumetric water content of the sand layer at point locations across the green, a technique was developed that combined (1) depth (or thickness) of the sand layer measured with a steel shaft tile probe, (2) radar signal two-way travel time from the base of the sand layer obtained using a ground-penetrating radar (GPR) system with 900 MHz antennas, and (3) an empirical equation relating porous media dielectric constant to water content. To test this technique, two GPR surveys were conducted on the Nursery Green at the Double Eagle Golf Club near Galena, Ohio, and two additional GPR surveys were carried out on the 9th Hole Green at the Delaware Golf Club near Delaware, Ohio. For comparison, time-domain reflectometry (TDR) water content values for the sand layer near the ground surface were obtained concurrent with each of the four GPR surveys.

Results of the four golf course green GPR/TDR surveys carried out on September 8 and 9, 2014 (Double Eagle Golf Club - before and after irrigation, respectively), and April 21 and 29, 2015 (Delaware Golf Club) show that the sand layer water contents determined with GPR respectively averaged, 18.8%, 25.2%, 12.2%, and 11.3%, which were quite similar to the respective TDR sand layer water content averages of 20.3%, 25.7%, 11.0%, and 14.1%. The spatial correlation coefficients (r) between the GPR-based sand layer water content values versus the TDR sand layer water content values for these four GPR/TDR surveys were 0.76 (September 8, 2014), 0.73 (September 9, 2014), 0.55 (April 21, 2015), and 0.70 (April 29, 2015). Sand layer water content was found to have moderate inverse spatial correlation with ground surface elevation ($r = -0.44$ to -0.56) and elevation at the base of the sand layer ($r = -0.43$ to -0.53). Consequently, the findings of this study clearly indicate that if sand layer depth values are available, then GPR can be utilized in a non-destructive manner to accurately map sand layer water content across a golf course green, and conversely, in cases where sand layer water content (hence, radar velocity) spatial patterns are already known, then this information can be employed to provide more accurate GPR-based sand layer depth values.

Introduction

Research Rationale

As of 2012, there were over 15,000 golf course facilities in the U.S.A. (National Golf Foundation, 2013). The upkeep of these facilities requires continual maintenance and occasional remodeling. The superintendents and architects responsible for these maintenance and remodeling efforts need non-destructive tools for obtaining information on shallow subsurface conditions and features, particularly on the golf course greens. Specifically, information on the distribution of water content across the sand layer component of a golf course green can be useful for assessing the effectiveness of the soil drainage system on different parts of the green and for scheduling uniform or spatially variable irrigation of the green. Proper drainage and irrigation are critical for

 DOI: #10.2113/JEEG21.4.215

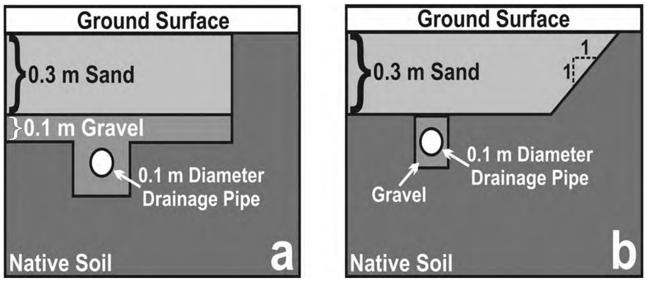

Figure 1. Golf course green design characteristics: a) United States Golf Association (USGA) Method and b) California (CAL) Method.

preserving the turfgrass of the golf course green in good playing condition. Near-surface geophysical methods, especially ground-penetrating radar (GPR), can potentially provide a non-destructive means for golf course superintendents and architects to measure the shallow sand layer water content. Furthermore, if the feasibility of a near-surface geophysical method, such as GPR, is demonstrated to be effective for sand layer water content measurement, then the possibility exists for future development of low cost sensors integrated with golf course maintenance equipment that could be employed to obtain time-sensitive shallow hydrologic data useful for spatially variable irrigation of the greens.

Golf Course Green Design Characteristics

Two of the most popular approaches to golf course green construction are the United States Golf Association (USGA) Method and the California Method (Hurdzan, 2004, 2006). The notation to be used throughout the article to designate golf green construction type will be USGA for United States Golf Association greens and CAL for California greens. Design recommendations for the USGA green call for a 30 cm uppermost layer of turfgrass-covered sandy material (often referred to as the "root zone") that is underlain by a 10 cm gravel layer resting on native soil subgrade. Gravel-backfilled trenches, typically 20 cm deep and 25 cm wide, containing circular cross-section 10 cm diameter drainage pipe are cut into the native soil subgrade (Fig. 1(a)) (Hurdzan, 2004, 2006). At the edge of a USGA green, the side interface between the sand and gravel layers and the native soil is vertical (Fig. 1(a)).

Design recommendations for the CAL green call for just the 30 cm turfgrass-covered layer of sandy material (*i.e.,* root zone) resting directly over the native soil subgrade, into which gravel-backfilled trenches have been cut containing circular cross-section 10 cm diameter drainage pipe (Fig. 1(b)). The drainage pipe trenches cut into the native soil are typically 20 cm deep and 15 cm wide (Hurdzan, 2004, 2006). The lateral edge of the sand layer within a CAL green is sloped (Fig. 1(b)), often at an angle of 45 degrees.

The drainage pipe network configuration varies for USGA or CAL greens, and rectangular or herringbone patterns are frequently employed. For the rectangular pattern, the drainage pipe laterals merge with the main collector pipe at an angle of 90 degrees. For the herringbone pattern, the drainage pipe laterals merge with the main collector pipe at an angle less than 90 degrees. The spacing distance between the circular cross-section drainage pipe laterals within a green is usually between 3 to 5 m (United State Golf Association, 2004; Boniak *et al.*, 2008). Modified versions of a CAL green often use flat, rectangular cross-section drainage pipes (30 or 46 cm wide and height of 4 cm) that are placed directly over top of the native soil subgrade, with a spacing distance between adjacent drain lines less than 6 m (Hurdzan, 2004, 2006). Corrugated, high-density, polyethylene tubing has been available since the mid-1960′s and is now used for both the circular and rectangular cross-section drainage pipes installed on golf course greens.

Previous Research

Allred *et al.* (2005, 2008), Boniak *et al.* (2008), and Freeland *et al.* (2014) demonstrated that GPR worked well on USGA and CAL greens for mapping below ground drainage pipe systems. GPR also exhibited a capability for measuring depth to the base of sand and gravel layers in the USGA and CAL greens that were investigated. In particular, Allred *et al.* (2005) found that GPR antennas with center frequencies between 250 and 1000 MHz were effective for locating golf course green drainage pipes, while GPR antennas with higher frequencies of 900 and 1000 MHz were best for resolving the thicknesses and depths of sand and gravel layers.

The use of GPR to determine the volumetric water content of soils has recently been a very active area of research (Galagedara *et al.*, 2003a, b; Huisman *et al.*, 2003; Bradford, 2008; Farmani *et al.*, 2008; Grote *et al.*, 2010; Grote, 2013). Figure 2 shows three popular means of measuring soil water content using GPR. One method uses the GPR ground wave, which travels through the shallow subsurface directly between the transmitting (Tx) and receiving (Rx) antennas. With an optimized separation distance between the antennas, the travel time for the ground wave can be measured (Fig. 2(a)), and since the antenna separation distance (S) is known, the radar signal velocity in the soil is easily calculated. The soil dielectric constant can be determined from the soil

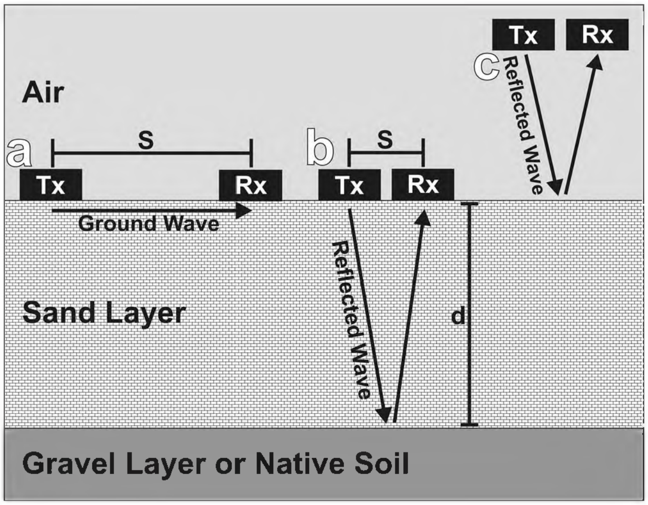

Figure 2. Potential approaches for determining golf course green sand layer water content using GPR: a) ground wave radar signal measurement, b) measurement of radar signal reflected from base of sand layer, and c) measurement of radar signal reflected from ground surface.

radar velocity, and the soil dielectric constant is then used with empirical or volumetric mixing model relationships to obtain soil volumetric water content values (Grote, 2013). Another method uses reflections from a feature buried at a known depth (*d*). Using this depth, along with the Tx to Rx separation distance (*S*), the measured two-way travel time of the radar signal that reflects off the buried feature (Fig. 2(b)) can be used to calculate the average radar velocity for the soil between the ground surface and the buried feature. Again, once the soil radar velocity is determined, the soil dielectric constant can be computed and subsequently used with a petrophysical relationship to obtain soil volumetric water content values (Grote, 2013). The third method uses a Tx and Rx positioned above the ground surface (Fig. 2(c)), and the amplitude of the radar signal reflected from the soil surface can be employed to determine the soil dielectric constant near the ground surface, which can then be used to estimate soil water content (Grote, 2013).

Research Objective and Hypothesis

The sand layer component of a golf course green (*i.e.*, root zone) extends from the turfgrass covered ground surface down to a depth of approximately 30 cm (Fig. 1). Proper sand layer drainage and irrigation are critical for keeping the turfgrass in good playing condition. In order to make the best management decisions regarding drainage system modifications or irrigation scheduling, it is preferable to measure a bulk or average water content over the complete thickness of the sand layer. Ground-penetrating radar signal reflections can potentially be employed to measure the average water content for the total thickness of the sand layer from the ground surface down to its base (Huisman *et al.*, 2003), and this approach has an advantage over the time-domain reflectometry (TDR) method employing fixed length waveguides that do not account for sand layer thickness variability. Using the GPR approach illustrated in Fig. 2(b), the water content within the sand layer at point locations across the green can be determined using the depth (or thickness) of the sand layer (found using a steel shaft tile probe), the radar signal two-way travel time from the base of the sand layer, and a petrophysical relationship between porous media dielectric constant and water content. The GPR soil water content measurement approach depicted in Fig. 2(b) had not previously been tested on golf course greens, so the governing objective of the study was to evaluate the feasibility of this GPR-based technique for measuring the water content across the sand layer on both USGA and CAL greens. A formal research hypothesis can be stated as follows: "An approach combining tile probe depth measurements, GPR travel time data, and an empirical relationship between dielectric constant and volumetric water content can be employed to accurately measure the bulk water content in the sand layer across a golf course green."

Materials and Methods

Test Site Locations

A golf course green investigation on the feasibility of GPR to measure sand layer water content was carried out at two test site locations shown in the Fig. 3 aerial images obtained from Google Earth (Google Inc., Mountain View, California). The first test site location was the Nursery Green at the Double Eagle Golf Club near Galena, Ohio (Latitude: 40.23846341, Longitude: –82.94241488, Fig. 3(a)). The United States Golf Association (USGA) Method (Fig. 1(a)) was used in constructing the Double Eagle Golf Club Nursery Green (from now on referred to as Double Eagle GC), which has a fairly flat surface area of 430 m^2 (maximum slope of 2.0°). This particular green was maintained solely for providing patches of turfgrass sod to other greens on the golf course. A prior GPR investigation using 400 MHz antennas mapped the drainage pipe network for the Double Eagle GC (solid white lines in Fig. 3(a)). This subsurface drainage system, comprised of circular, 10 cm diameter, corrugated plastic tubing (CPT), had two

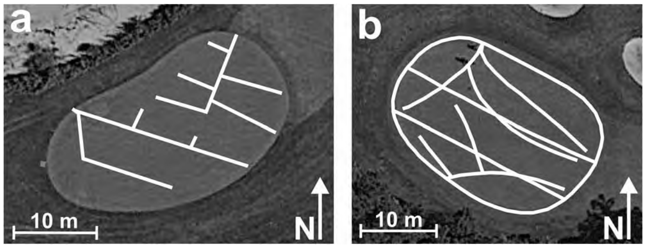

Figure 3. Aerial images of golf course green site locations obtained from Google Earth: a) Double Eagle GC and b) Delaware GC. The drainage pipe network for each green is represented with solid white lines.

outlets (Fig. 3(a)), which is a fairly common golf course green construction practice.

The second test site location was the 9th Hole Green at the Delaware Golf Club near Delaware, Ohio (Latitude: 40.25024736, Longitude: –83.05174583, Fig. 3(b)). The California Method (Fig. 1(b)) was used in constructing the Delaware Golf Club 9th Hole Green (referred to as Delaware GC), which has a fairly flat surface area of 450 m^2 (maximum slope of 2.5°). A prior GPR investigation using 400 MHz antennas mapped the drainage pipe network for the Delaware GC (solid white lines in Fig. 3(b)). This drainage pipe network was comprised of rectangular cross-section (30 cm by 4 cm) CPT. The original subsurface drainage system installed did not function properly, and as a consequence, further modifications were required, resulting in the rather complex drainage pipe pattern with a newer pipe integrated with an older pipe network and what appears to be two drainage outlets (Fig. 3(b)).

Equipment

The approach tested in this investigation to determine the bulk water content in the sand layer across a golf course green involved combining tile probe depth measurements, GPR travel time data, and an empirical relationship between dielectric constant and volumetric water content. Physical sampling to confirm water content values obtained using the GPR approach would have required collecting a large number of sand layer cores (between 100 to 200 on each green), which was totally unacceptable to the golf course superintendents in charge of green maintenance. Since soil samples could not be obtained to confirm the GPR based water content values, time-domain reflectometry (TDR) was used as an alternative to provide at least some confirmation of the GPR approach with regard to the magnitude of the water content values and the general spatial pattern of sand layer water content across the

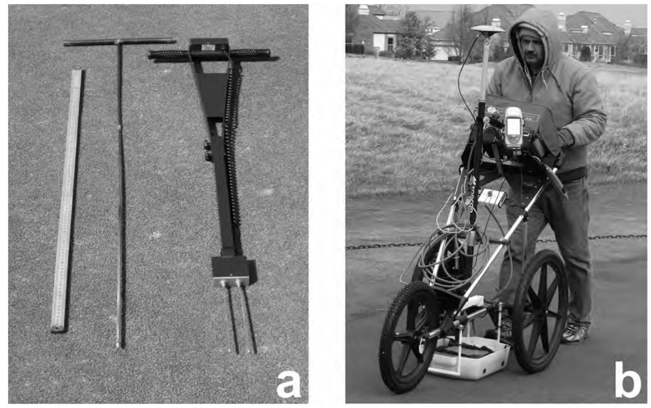

Figure 4. Equipment: a) left side of photo - 1 m ruler and a 1.2 m steel shaft tile probe, right side of photo - Spectrum Technologies, Inc. Field Scout TDR-300 with 20 cm waveguides, and b) Geophysical Survey Systems, Inc. SIR-3000 GPR System using 900 MHz antennas integrated with a Topcon Positioning Systems, Inc. RTK rover system and attached PG-S1 external GPS antenna.

green. Depth to the base of the golf course green sand layer was measured with a ruler and a 1.2 m steel shaft tile probe (Forestry Suppliers, Inc, Jackson, Mississippi, Fig. 4(a)). Radar signal travel time data were obtained using a GSSI SIR-3000 GPR System with 900 MHz antennas (Geophysical Survey Systems, Inc., Nashua, New Hampshire, Fig. 4(b)). The TDR water content values were collected using a Field Scout TDR-300 with 20 cm waveguides (Spectrum Technologies, Inc., East Plainfield, Illinois, Fig. 4(a)). The 20 cm waveguides were the longest available for this particular probe. The TDR probe therefore provided average volumetric water content values for only the top 20 cm of the golf course green sand layer. Real-time kinematic (RTK) global positioning system (GPS) technology was employed to provide accurate latitude and longitude coordinates for the depth, GPR, and TDR measurements. Surface elevation data for the golf course greens were also obtained with RTK-GPS concurrent with depth measurements. The RTK-GPS data was acquired using a Topcon Positioning Systems, Inc. (Livermore, CA) GRS-1 RTK rover system (with PG-S1 external antenna attached) receiving network corrections in real time from the Ohio Department of Transportation VRS CORS network (Fig. 4(b)). Horizontal coordinates were referenced to the datum NAD 83 (2011) Epoch 2010.0, and vertical coordinates to the datum NAVD 88.

Data Collection Procedures

In advance of collecting GPR and TDR data at the test site locations, depth measurements to the bottom of the sand layer (Fig. 1) were obtained using a ruler and a tile probe (Fig. 4(a)). These depth measurements involved a simple process by which the steel shaft of the tile probe was pushed into the ground, and once the tip of the shaft encountered the bottom of the sand layer, a ruler was then used to measure the length of the steel shaft inserted beneath the surface. For a golf course green constructed with the USGA Method (*e.g.,* Double Eagle GC), it became almost impossible to push the probe any further into the ground once the steel shaft tip encountered the interface between the sand and gravel layer. For a CAL golf course green (*e.g.,* Delaware GC), once the steel shaft tip encountered the interface between the sand layer and the underlying native clayey soil, pushing the probe further into the ground became noticeably easier. The depth to the base of the sand layer was measured at 65 locations for the Double Eagle GC and at 93 locations for the Delaware GC.

There were four GPR/TDR surveys carried out for this study; two at the Double Eagle GC and two at the Delaware GC. The GPR and TDR surveys at the Double Eagle GC were first conducted on September 8, 2014 and then next on September 9, 2014 after two hours of sprinkler irrigation the night before. The GPR and TDR surveys at the Delaware GC were first conducted on April 21, 2015, and then next on April 29, 2015. During the period between the GPR/TDR surveys, the Delaware GC experienced a relatively cool average temperature of 8.6° C along with 1.1 cm of rainfall (Ohio Agricultural Research and Development Center, 2015), and as a consequence, there was no irrigation needed for the green. For each of the four GPR surveys, data were collected in a single transect having a decreasing spiral pattern that started along the outside perimeter of the green and ended at the center of the green. A GPR signal trace (amplitude versus travel time) was obtained every 2.5 cm along the transect. Concurrent with the GPR data collection, water content measurements were obtained with the TDR probe (Fig. 4(a)) at point locations across the green. There were between 40 to 55 water content values obtained for each of the four TDR surveys.

Data Analysis

GPR data processing was minimal and only included radar signal amplification. RADAN 7 (Geophysical Survey Systems, Inc., Nashua, New Hampshire) was the computer software used for the GPR data processing, data display, and for determining the travel time of the air wave and sand layer radar signals. Using the following equation (Grote, 2013), GPR survey data were used to calculate the actual two-way travel time, t_R, for the radar signal that is directed downwards from the GPR transmitting antenna (Tx) and subsequently reflected upwards from the base of the sand layer to the GPR receiving antenna (Rx):

$$t_R = t_{Sand\ Layer\ Base} - \left(t_{Air\ Wave} - \frac{S}{c}\right), \quad (1)$$

where $t_{Sand\ Layer\ Base}$ is the travel time on the GPR signal trace for the radar reflection from the base of the sand layer (Figs. 5(a) and 5(b)), $t_{Air\ Wave}$ is the travel time on the GPR signal trace for the radar pulse traveling directly through the air between the transmitting and receiving antennas (Figs. 5(a) and 5(b)), S is the Tx to Rx separation distance (11 cm for the 900 MHz antennas used in this study), and c is the velocity of an electromagnetic wave in free space (29.98 cm/ns). For both the air wave and the sand layer reflection, the inflection (zero-amplitude point) preceding the large GPR wavelet was chosen to export travel times. The inflection point was chosen to reduce dispersion that may occur when picking a point within the main GPR wavelet and to avoid superposition of the primary (first) reflection wavelet with reflections from underlying events. In Fig. 5(a), the reflection from the base of the sand layer is shown as white dots superimposed at the beginning of the white portion of the reflection wavelet (positive amplitude) in the GPR profile on the left of the figure. To the right, this same interface is shown using black dots on the signal trace. In Fig. 5(b), the reflection from the base of the sand layer is shown as white dots superimposed at the beginning of the black portion of the reflection wavelet (negative amplitude) in the GPR profile on the left of the figure. The polarity reversal is caused by differences in the water content of the underlying material. For Fig. 5(a), the sand is underlain by gravel, which has a lower water content at the time of this survey, resulting in a positive reflection coefficient. For Fig. 5(b), the sand is underlain by wetter native soil, resulting in a negative reflection coefficient.

The two-way travel time (t_R) was determined at points along the GPR traverse, and maps of t_R were created using Surfer 8 (Golden Software, Inc., Golden, Colorado). The spatial interpolation method Multiquadratic Radial Basis Function Method (Golden Software, Inc., 2002) was used to interpolate values of t_R to locations where the thickness of the sand layer (d) was known from steel shaft tile probe measurements. The average radar velocity, v, over the total depth (thickness) of the golf course green sand layer was calculated using t_R:

$$v = \frac{2\sqrt{d^2 + (0.5S)^2}}{t_R}. \quad (2)$$

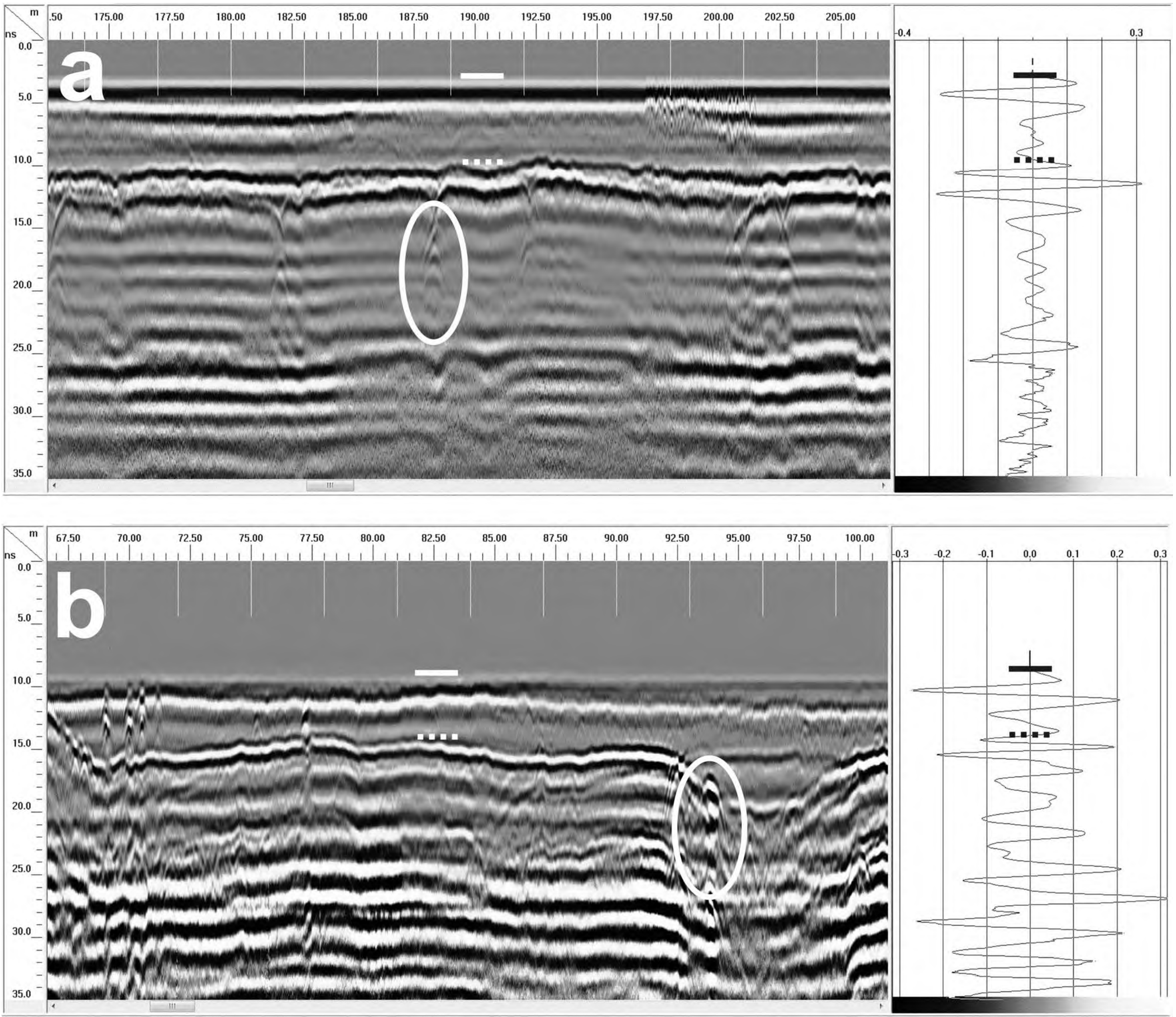

Figure 5. Examples of minimally processed GPR profiles and individual amplitude versus time radar signal traces with earliest arrival of $t_{Sand\ Layer\ Base}$ marked with short white or black dotted line segments and the earliest arrival of $t_{Air\ Wave}$ marked with short white or black solid line segments: a) data from Double Eagle GC and b) data from Delaware GC. Drainage pipe reflection hyperbola responses are highlighted with white line ovals.

The value of v at a point location on the green can be used to estimate the average sand layer dielectric constant, K, at that location using the relationship (Conyers, 2004):

$$K = \left(\frac{c}{v}\right)^2. \tag{3}$$

An empirical equation developed by Topp *et al.* (1980) using a wide variety of soil textures was then used with K to determine the average volumetric water content, θ, over the thickness of the sand layer at a particular point location on the green:

$$\theta = -0.053 + 0.00292K - 0.00055K^2 + 0.0000043K^3. \tag{4}$$

The golf course green sand layer is typically 80% quartz sand (0.05 mm to 2.0 mm particle size) with the remaining material comprised of gravel, silt, clay, and organic matter usually added as peat (Hurdzan, 2004). Although a number of empirical equations have been developed relating soil dielectric constant with soil volumetric water content (Roth *et al.*, 1992; Sutinen, 1992; Schaap *et al.*, 1996; Santamarina and Fam, 1997; da Silva *et al.*, 1998; Kaiser *et al.*, 2010), Topp's equation was used in this research because it is widely accepted and has been shown to be accurate for sandy soil materials (Drungil *et al.*, 1989; Seyfried and Murdock, 2004; Kelleners *et al.*, 2005; Robinson *et al.*, 2005; Take *et al.*, 2007), such as those found within the sand layer of golf course greens.

In summary, for each of the four GPR survey datasets, interpolated values of t_R were obtained at each location where the depth to base of the sand layer (d) had been previously measured. With d, t_R, and S known, Eqs. 1 through 4 were used to estimate sand layer θ at the point locations where d had been determined. Once calculated, these GPR derived θ values were mapped using Surfer 8 for each GPR survey. Again, at the same time that the four GPR surveys were conducted, TDR θ values for the sand layer near the ground surface (down to a depth of 20 cm) were also measured. Surfer 8 was later used to map these θ values for each TDR survey.

In the next step of the data analysis, interpolated values of GPR-based θ were obtained at the point locations that TDR θ was measured concurrent with the GPR survey. The interpolated GPR-based θ and the TDR θ from each GPR/TDR survey were then compared using averages, standard deviations, maximum values, minimum values, and spatial correlation coefficient (r) in order to evaluate the accuracy of the GPR water content measurement approach. The spatial correlation coefficient compares interpolated GPR-based θ with TDR θ at each measurement location to determine whether the sand layer spatial pattern of GPR-based θ across the green is similar to the sand layer spatial pattern of TDR θ.

The consistency of the water content distribution with time for each site was also considered. For the point locations where d was measured, r values were computed for GPR θ at Double Eagle GC on September 8, 2014 versus GPR θ at Double Eagle GC on September 9, 2014 and for GPR θ at Delaware GC on April 21, 2015 versus GPR θ at Delaware GC on April 29, 2015 in order to assess whether sand layer water content spatial patterns remained consistent over time. Also, r values were calculated for each GPR survey to evaluate the spatial correlation of GPR θ versus elevation at the ground surface (top of sand layer), GPR θ versus elevation at the base of the sand layer, and GPR θ versus thickness of the sand layer. This comparison was carried out to gain insight regarding the impact of certain sand layer characteristics on sand layer water content.

The data collected during this investigation also provided the opportunity to evaluate the impact of spatial variability of soil water content on the accuracy of soil layer depth/thickness estimates based on GPR measurements. In most GPR site investigations, it is the GPR data itself that are employed to determine thicknesses and depths of soil layers. The conversion of radar signal two-way travel time to depth is typically accomplished using a single representative value of radar signal velocity that is obtained via a reflection hyperbola curve fitting procedure, or possibly, conversion of the average soil volumetric water content to a soil radar velocity. The impact on the accuracy of GPR depth estimates due to using a single representative value of soil radar velocity, where substantial spatial variability of water content (and hence variability of soil radar velocity) exists, was evaluated in this study by comparing actual depths to the base of the sand layer (via tile probe) on both golf course greens to depth estimates from each of the four GPR surveys. For each GPR survey, a unique representative sand layer radar velocity was used to convert radar signal travel time to depth.

The representative sand layer radar velocity, v_{AVG}, used with a particular GPR survey data set to convert t_R values to base of sand layer depth estimates, was obtained by averaging the sand layer radar velocities across the green. Basically, for each GPR survey data set, depth to the base of the sand layer was estimated from t_R and v_{AVG} at the points coincident with locations measured with the tile probe. The depth difference (DD), absolute depth difference (DD_{ABS}), percent depth difference ($DD_{\%}$), and absolute percent depth difference ($DD_{ABS\text{-}\%}$) of the GPR-based depth estimate, d_{GPR}, relative to the actual depth, d, was calculated at each of these point locations for each GPR survey. The values of DD, DD_{ABS}, $DD_{\%}$, and $DD_{ABS\text{-}\%}$, were calculated at individual point locations across the golf course green using the equations:

$$DD = d_{GPR} - d, \tag{5}$$

$$DD_{ABS} = |d_{GPR} - d|, \tag{6}$$

$$DD_{\%} = \left(\frac{d_{GPR} - d}{d}\right)100, \tag{7}$$

$$DD_{ABS-\%} = \left|\left(\frac{d_{GPR} - d}{d}\right)\right|100, \tag{8}$$

The DD and $DD_{\%}$ values for each GPR survey were mapped spatially. Additionally, for each GPR survey, the average and standard deviation of the DD_{ABS} and the $DD_{ABS\text{-}\%}$ values, along with the maximum and minimum of DD and $DD_{\%}$ values, were determined to quantitatively evaluate the error in the GPR base of sand layer depth estimates that were calculated assuming an average sand layer radar velocity instead of accounting for the spatial variability of sand layer radar velocity caused by corresponding spatial variability in sand layer water content.

Results and Discussion

Evaluation of GPR Approach for Water Content Measurement

Figure 6 provides an example of the mapped results from investigating GPR capability for sand layer water content measurement. The maps shown in Fig. 6 are for the Double Eagle GC, mostly from data obtained on September 8, 2014, and includes measurement locations, surface elevation, depth to the base of the sand layer, actual GPR two-way travel time for radar signal reflected from the base of the sand layer, sand layer volumetric water content determined with time-domain reflectometery (TDR), and sand layer θ based on the GPR survey. The green-colored symbols in Fig. 6(a) clearly depict the spiral transect approach used to collect the GPR data. There was a maximum 30 cm elevation difference from southwest to northeast across the green (Fig. 6(b)). The Double Eagle GC exhibited substantial spatial variation in d (Fig. 6(c)), and on September 8, 2014 there was also considerable spatial variation in t_R (Fig. 6d). Both d and t_R (Figs. 6(c) and 6(d)) were used with Eqs. 2 to 4 to calculate the GPR-based θ, and GPR-based θ likewise exhibited substantial spatial variability (Fig. 6(f)). In comparison to the GPR-based θ, there was a similar spatial pattern in TDR θ (Fig. 6(e)).

Table 1 shows the average, standard deviation, maximum, and minimum values for d, t_R, v for both study sites. Both the Double Eagle GC and the Delaware GC exhibit considerable spatial variability in depth to the base of the sand layer. Both the USGA and CAL greens have a design recommendation that the sand layer have a thickness of 30 cm (Figs. 1(a) and 1(b)). As shown in Table 1, d for the Double Eagle GC averaged 32 cm, which is slightly greater that the design recommendation of 30 cm, and d for the Delaware GC averaged 37.5 cm, which is much greater than the design recommendation of 30 cm. There are three possible reasons that these two golf course greens on average have a sand layer thickness greater than 30 cm, especially the Delaware GC (E. McCoy, personal communication, September 10, 2015). First, before or during construction, the golf course architect may have an original design or make design changes that call for the sand layer to be thicker (or thinner) than 30 cm in different parts of the green. (Note: This might also possibly explain why sand layer thickness was substantially less than 30 cm at a few locations along the perimeter of the Double Eagle GC). Second, periodic topdressing of the green with sand to improve turfgrass conditions will increase the sand layer thickness over time. Third, for golf course greens with adjacent bunkers, such as the Delaware GC, playing the golf ball out of the bunker and onto the green will dislodge sand from the bunker that is then deposited on the green, which over time, will increase the sand layer thickness on parts of the green close to the bunkers.

The Table 1 standard deviation, maximum, and minimum values for t_R indicate that, for each of the four GPR surveys, there was substantial variation of t_R across the golf course green. Both d and t_R were used with Eq. 2 to calculate v and the variability in these parameters led to fairly high variability in v across the green for all four GPR surveys. Average t_R for each of the Double Eagle GC GPR surveys were greater than the average t_R for each of the Delaware GC GPR surveys, even though the average sand layer thickness was greater for the Delaware GC. The longer travel time at the Double Eagle GC reflects the lower v at this site.

For each GPR survey, Eqs. 3 and 4 were used to calculate θ from v at each location where d had been measured. Next, interpolated GPR θ values were obtained at all locations that TDR θ was measured for each GPR/TDR survey. A comparison of interpolated GPR θ with TDR θ is provided in Table 2. The results for average, standard deviation, maximum, minimum, and spatial correlation coefficient in Table 2, show that, with respect to each GPR/TDR survey, GPR- and TDR-based average water content, variability, and spatial pattern were generally quite similar to one another. Regarding just the magnitude and variability of θ, as indicated by the average, standard deviation, maximum, and minimum θ results in Table 2, GPR θ and TDR θ were closest with respect to the survey at the Double Eagle GC on September 9, 2014 and were furthest apart with respect to the two surveys at the Delaware GC on April 21 and 29, 2015. The GPR θ and TDR θ spatial patterns correlated fairly well ($r \geq 0.7$) at the Double Eagle GC on September 8 and 9, 2014 and at the Delaware GC on April 29, 2015, while a moderate spatial correlation ($r = 0.55$) was found between GPR θ and TDR θ at the Delaware GC on April 21, 2015. It is important to note that GPR θ represents the water content over the entire thickness of the sand layer, while

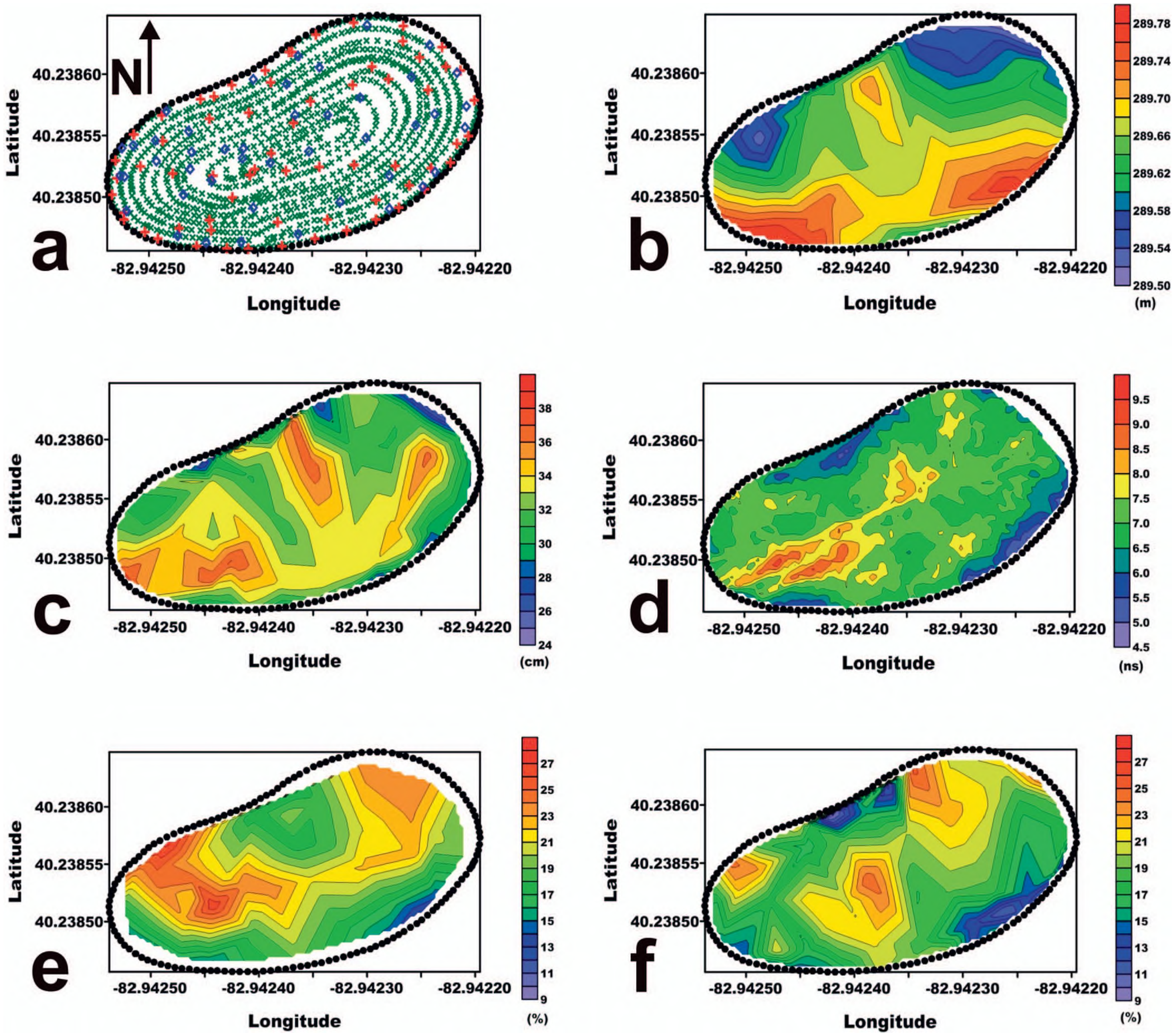

Figure 6. Example of mapped results from this investigation obtained at the Double Eagle GC: a) measurement locations with data points for surface elevation and depth to base of sand layer, *d*, represented by red symbols, GPR two-way travel time, t_R, for radar signal reflected from base of sand layer represented with green symbols, and TDR volumetric water content, θ, represented by blue symbols; b) surface elevation in meters obtained in advance of GPR/TDR surveys); c) *d* in centimeters obtained in advance of GPR/TDR surveys); d) t_R in nanoseconds (September 8, 2014); e) sand layer θ in percent determined with TDR (September 8, 2014); and f) GPR-based sand layer θ in percent calculated at the measurement locations for *d* (September 8, 2014).

TDR θ is representative of the water content in only the upper 20 cm of the sand layer. Consequently, although GPR θ and TDR θ represent different volumes of material, the similarity within each GPR/TDR survey of GPR- and TDR-based θ magnitude, variability, and spatial pattern clearly confirms that the GPR-based approach used in the this study can accurately determine water content conditions in golf course green sand layers

Differences in GPR θ and TDR θ at individual point locations across the two greens were likely a result of differences between the upper sand layer volumetric water content (surface down to a depth of 20 cm), which was measured with TDR, and the lower sand layer volumetric water content (from a depth of 20 cm down to the base of the sand layer), which strongly impacted GPR θ (since GPR θ represents the entire thickness of

Table 1. Statistics for depth to the base of the sand layer (d), two-way travel time for radar signal reflected from the base of the sand layer (t_R), and sand layer radar velocity (v).[a]

Location	Date	Average and (Std. Dev.) of d (cm)	Maximum and (Minimum) of d (cm)	Average and (Std. Dev.) of t_R (ns)	Maximum and (Minimum) of t_R (ns)	Average and (Std. Dev.) of v (cm/ns)	Maximum and (Minimum) of v (cm/ns)
Double Eagle GC	09/08/2014	32.0 (2.9)	39.0 (24.7)	6.72 (0.80)	8.58 (4.88)	9.75 (1.00)	12.81 (8.09)
Double Eagle GC	09/09/2014	same as above	same as above	7.82 (0.78)	9.87 (5.82)	8.34 (0.66)	10.17 (7.17)
Delaware GC	04/21/2015	37.5 (3.6)	47.3 (31.0)	6.63 (1.01)	10.01 (5.22)	11.57 (1.25)	14.29 (8.36)
Delaware GC	04/29/2015	same as above	same as above	6.36 (0.94)	9.99 (5.06)	12.04 (1.24)	14.78 (8.38)

[a] Both t_R and v were determined at golf course green point locations where d was measured. There were 65 point locations at the Double Eagle GC where d, t_R, and v were measured or calculated. There were 93 point locations at the Delaware Golf Club GC where d, t_R, and v were measured or calculated.

the sand layer). The magnitude and variability of GPR θ and TDR θ, based on average, standard deviation, maximum, and minimum results in Table 2, did not show dramatic changes at the Delaware GC from April 21 to April 29, 2015, which was to be expected. During this period, there was very little water added or removed from the green, due to a 1.1 cm of rainfall, no irrigation, and a cool average temperature (8.6 °C) that limited turfgrass evapotranspiration. The variations in GPR- and TDR-based θ water content on April 21 and 29, 2015 again likely reflect vertical changes in water content since the sampling depths for the two methods differ. At the Delaware GC site, the GPR measures, on average, a layer almost twice as thick as that measured by TDR (average of 37.5 cm for GPR versus 20 cm for TDR). For the Double Eagle GC from September 8 to September 9, 2014, Table 2 shows that GPR and TDR measured a substantial increase in θ, since the GPR/TDR survey on September 8 was carried out prior to sprinkler irrigation of the green, and the GPR/TDR survey on September 9 was conducted shortly after irrigation of the green. Consequently, these results indicate that GPR can be effective in monitoring changes in sand layer water content over time due to significant rainfall/irrigation events and subsequent drainage.

Because of capillary processes associated with having a gravel layer beneath the sand layer, a golf course green constructed using the USGA Method (*e.g.*, Double Eagle GC) is designed to hold more water within the sand layer as compared to a golf course CAL green (*e.g.*, Delaware GC), which tends to have a sand layer that drains more thoroughly (E. McCoy, personal communication, September 11, 2015). The more complete sand layer drainage that typically occurs with a CAL green explains why GPR θ and TDR θ were substantially higher at the Double Eagle GC versus the Delaware GC (Table 2). By being able to measure water content through the entire thickness of the sand layer, the GPR approach used in this research is very well adapted for assessing whether a USGA green is meeting one its critical design goals of being able retain an optimal amount of water within the sand layer.

Table 2. Comparison of TDR and GPR sand layer volumetric water content.[a]

Location	Date	Average and (Std. Dev.) of TDR θ (%)	Maximum and (Minimum) of TDR θ (%)	Average and (Std. Dev.) of Interpolated GPR θ (%)	Maximum and (Minimum) of Interpolated GPR θ (%)	Spatial Correlation Coefficient - r - TDR θ Versus Interpolated GPR θ
Double Eagle GC	09/08/2014	20.3 (3.6)	27.6 (12.6)	18.8 (2.7)	23.7 (12.7)	0.76
Double Eagle GC	09/09/2014	25.7 (2.3)	29.5 (20.1)	25.2 (2.3)	29.1 (19.2)	0.73
Delaware GC	04/21/2015	11.0 (1.7)	15.0 (6.4)	12.2 (3.0)	21.9 (7.6)	0.55
Delaware GC	04/29/2015	14.1 (2.5)	21.6 (9.3)	11.3 (2.9)	18.8 (7.6)	0.70

[a] GPR θ was interpolated at golf course green point locations where TDR θ was measured. Consequently, for comparing TDR θ and interpolated GPR θ, there were 44 point locations at the Double Eagle GC on September 8, 2014, 40 point locations at the Double Eagle GC on September 9, 55 point locations at the Delaware GC on April 21, 2015, and 40 point locations at the Delaware GC on April 29, 2015

Table 3. Spatial correlation between GPR sand layer water content measurements versus elevation at ground surface, elevation at base of sand layer, or thickness of sand layer.[a]

		Spatial Correlation Coefficient - r		
Location	Date	GPR θ Versus Elevation at Ground Surface	GPR θ Versus Elevation at Base of Sand Layer	GPR θ Versus Thickness of Sand Layer
Double Eagle GC	09/08/2014	−0.56	−0.53	−0.17
Double Eagle GC	09/09/2014	−0.53	−0.45	−0.27
Delaware GC	04/21/2015	−0.44	−0.43	0.03
Delaware GC	04/29/2015	−0.45	−0.43	−0.02

[a] GPR θ and elevation at the ground surface were obtained at the same golf course green point locations where sand layer thickness (same as depth to the base of the sand layer, d) was measured. Elevation at the base of the sand layer was calculated by subtracting d from ground surface elevation. There were 65 point locations at the Double Eagle GC where GPR θ, ground surface elevation, elevation at base of sand layer, and d were measured or calculated. There were 93 point locations at the Delaware GC where GPR θ, ground surface elevation, elevation at base of sand layer, and d were measured or calculated.

General Considerations on Using GPR Versus TDR for Measuring Sand Layer Water Content

The overall project goal was to develop an accurate and efficient method for mapping the golf course green sand layer average volumetric water content through the total thickness of the sand layer from the ground surface down to the base. Accomplishing this goal is not very practical using TDR, because of the typical non-uniformity of sand layer thickness across the green. Using TDR to accurately measure average sand layer volumetric water content at a particular location on a golf course green would require the TDR probe waveguide length to equal the depth to the base of the sand layer. If the waveguides are too long, then the measured water content is influenced by the water content of the soil and/or gravel beneath the sand layer. If the waveguides are too short, then the measured water content may not truly reflect the average water content for the complete sand layer thickness. Consequently, due to non-uniform sand layer thickness across the green, a range of TDR waveguide lengths would be needed to accurately map average sand layer water content across the green. In this case, the lengths would need to range from 25 cm to 47 cm. Furthermore, at each measurement location, depth to the base of the sand layer would first need to be determined using a tile probe and then waveguides with a length corresponding to this depth installed on the TDR probe to get the sand layer water content. Using TDR to map the average water content of the sand layer thickness across the golf course green would therefore become very tedious and time consuming. Combining data from two separately conducted surveys, (1) sand layer depth measurements with a tile probe, and (2) GPR two-way travel time to the base of the sand layer, is a much more time efficient method to map the average water content of the sand layer thickness across the green.

Assessment of Water Content Spatial Pattern Consistency Over Time and the Impact of Sand Layer Characteristics on Water Content

With respect to GPR θ, the sand layer water content spatial pattern on a golf course green appears to stay fairly consistent over time as indicated by a r of 0.81 for GPR θ at the Double Eagle GC on September 8, 2014 versus GPR θ at the Double Eagle GC on September 9, 2014 and a r of 0.92 for GPR θ at Delaware GC on April 21, 2015 versus GPR θ at Delaware GC on April 29, 2015. Spatial correlation was also evaluated for each GPR survey between GPR θ versus elevation at the ground surface (top of sand layer), GPR θ versus elevation at the base of the sand layer, and GPR θ versus thickness of the sand layer. Results of this correlation analysis are provided in Table 3. The r values in Table 3 show a moderate inverse spatial correlation between θ and elevation at the ground surface ($r = -0.44$ to -0.56) and between θ and elevation at the base of the sand layer ($r = -0.43$ to -0.53). The probable explanation for the inverse relationship between sand layer θ versus ground surface elevation or elevation at the base of the sand layer is that (1) rainfall/irrigation runoff will flow towards and concentrate in low surface elevation areas, which produces high sand layer θ beneath these areas, while furthermore, (2) subsurface water can build up at the sand/gravel or sand/soil interface to the point that there is gravity driven flow towards and accumulation in low elevation areas at the base of the sand layer, which in turn produces high sand layer θ where these areas are present in the base of sand layer (Prettyman and McCoy, 2003). There was very little spatial correlation between θ and thickness of the sand layer (r = 0.03 to –0.27). Therefore, ground surface topography and topography at the base of the sand layer have some impact on θ, but the influence of sand layer thickness on θ is negligible.

A visual comparison of the drainage pipe network configuration (Fig. 3(a)) to the GPR θ maps from Double Eagle GC (September 8 and 9, 2014) offered no indication that improperly functioning drainage pipes affected sand layer θ spatial patterns. Likewise, a visual comparison of the drainage pipe network configuration (Fig. 3(b)) to the GPR θ maps from Delaware GC (April 21 and 29, 2015) offered no indication that improperly functioning drainage pipes affected sand layer θ spatial patterns. Additionally, it is reasonable to assume that the spatial pattern of sand layer θ could be influenced by other factors, such as spatial variation in sand layer particle size distribution and sand layer compaction. Essentially, due to capillary processes, a finer grained sand will retain more water than a coarser grained sand (Bohn *et al.*, 1985), while the impact of compaction on sand layer water holding capacity is somewhat unclear. More investigation is needed on the impact of these factors in regard to sand layer θ. However, most importantly, since sand layer θ patterns remain consistent over time, it is now evident that a single GPR survey can provide important insight on which parts of the green that the sand layer is draining best and which parts of the green that the sand layer is draining poorly.

Importance of Considering Soil Water Content Variability for Accurate Depth Estimation

The set of data collected during this investigation provided an opportunity to evaluate the impact of spatial variability of soil water content, and hence the spatial variability of soil radar velocity, on the accuracy of soil layer depth/thickness estimates based on GPR measurements. Depth estimates from GPR data are typically computed using an average radar velocity for the subsurface, but this approach can potentially lead to errors in depth estimates when there is significant spatial variability in the subsurface radar velocity due to spatial variability in subsurface volumetric water content. Figure 7 provides an example of the mapped results from this evaluation of GPR sand layer depth estimate errors due to using an average sand layer radar velocity and not accounting for the spatial variability in sand layer radar velocity caused by spatial variability in sand layer θ. The maps shown in Fig. 7 are for the Delaware GC, and with the exception of Fig. 7(c) (actual sand layer depth), are directly related to GPR data collected on April 29, 2015. The maps include sand layer water content determined from GPR data (Fig. 7(a)), sand layer radar velocity (Fig. 7(b)), actual depth to base of sand layer measured using a tile probe (Fig. 7(c)), GPR estimated depth to base of sand layer based on using an average value for v (Fig. 7(d)), difference, DD, between d_{GPR} and d as defined by Eq. 5 (Fig. 7(e)), and percent difference, $DD_{\%}$, between d_{GPR} and d as defined by Eq. 7 (Fig. 7(f)). The actual depth to the base of the sand layer differs substantially from the GPR estimated depth to the base of the sand layer that is based on using an average value for v. Accordingly, DD and $DD_{\%}$ can be quite large as depicted in Figs. 7(e) and 7(f), respectively.

Table 4 shows errors in the base of the sand layer depth estimates from each of the four GPR surveys that would result from using an average value of v to convert t_R to depth. The average of the absolute value of the depth difference, DD_{ABS} ranged from 2.0 cm to 3.5 cm for the four GPR surveys. The average of the absolute value of the percent depth difference, $DD_{ABS\text{-}\%}$, ranged from 6.4% to 9.3% for the four GPR surveys. The greatest depth estimate error was 18.4 cm, or 44.4% for a location in the northwest part of the Delaware GC using GPR data from April 29, 2015 (Figs. 7(e) and 7(f), Table 4). Again, employing radar signal two-way travel time to determine depth is typically accomplished using a single representative (average) value of radar signal velocity that is obtained via a reflection hyperbola curve fitting procedure, or possibly, converting the average of soil volumetric water content measurements (via TDR) to a soil radar velocity. The results presented in Fig. 7 and Table 4 clearly indicate that using an average value of subsurface radar velocity can lead to large depth estimate errors when there is substantial spatial variability in subsurface radar velocity due to spatial variability in subsurface θ. Alternatively, if the spatial distribution of subsurface radar velocity can be determined at a sufficient number of locations via reflection hyperbola curve fitting or water content measurements, then the spatial pattern of GPR two-way travel time and the spatial pattern of subsurface radar velocity can be combined to accurately map the depth to buried features.

Recommendations for Future Research

Two future research projects are suggested. First, the water content measurement accuracy of the GPR based approach highlighted in this article can possibly be improved through efforts devoted to development of an empirical equation relating dielectric constant to water content that is specific to golf course green sand layer

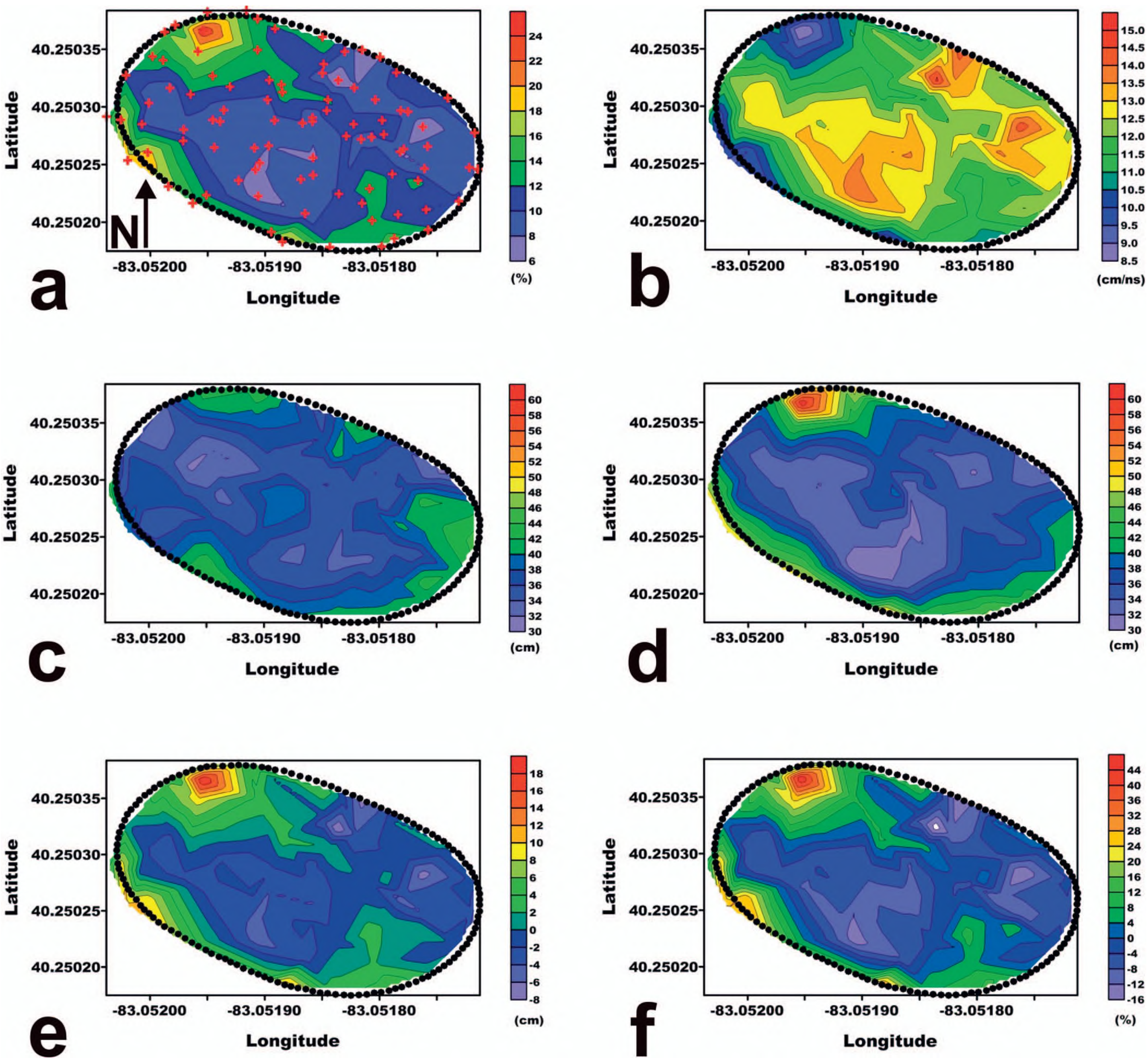

Figure 7. Mapped results from the Delaware GC depicting GPR sand layer depth estimate errors due to using an average sand layer radar velocity and not accounting for the spatial variability in sand layer radar velocity that is caused by spatial variability in sand layer water content: a) sand layer water content, *θ*, in percent previously determined from GPR data (April 29, 2015); b) sand layer radar velocity, *v*, in nanoseconds/centimeter (April 29, 2015); c) actual depth in centimeters to base of sand layer, *d*, measured with a tile probe; d) GPR estimated depth in centimeters to base of sand layer, d_{GPR}, based on using an average value of *v* April 29, 2015) ; e) difference, *DD*, in centimeters between d_{GPR} and *d* as defined by Eq. 5 (April 29, 2015); and f) percent difference, *DD%*, between d_{GPR} and *d* as defined by Eq. 7 (April 29, 2015).

materials. Second, multi-channel GPR systems could provide a greater density of measurement points and potentially allow integration of both ground wave and reflected wave methods (depending set-up of transmitting and receiving antennas) to obtain information on vertical changes in water content, while also reducing the time needed to conduct a golf course green GPR survey. Results from both projects would allow the more efficient collection of more GPR data, improved accuracy of sand layer water content estimates, and insight on the vertical distribution of water in the sand layer after drainage and irrigation.

Table 4. Error in estimating depth to base of sand layer due to ignoring the spatial variability in soil radar velocity that is a function of water content.

Location	Date	Average and (Std. Dev) of DD_{ABS}[a] (cm)	Average and (Std. Dev.) of $DD_{ABS\text{-}\%}$[b] (%)	Maximum and (Minimum) of DD[c] (cm)	Maximum and (Minimum) of $DD_{\%}$[d] (%)
Double Eagle GC	09/08/2014	2.6 (1.9)	8.3 (5.8)	6.2 (−8.5)	21.2 (−24.7)
Double Eagle GC	09/09/2014	2.0 (1.5)	6.4 (4.8)	5.3 (−6.7)	16.8 (−18.5)
Delaware GC	04/21/2015	3.5 (3.0)	9.3 (7.5)	16.2 (−7.7)	38.9 (−19.5)
Delaware GC	04/29/2015	3.3 (3.0)	8.7 (7.6)	18.4 (−7.8)	44.4 (−18.9)

[a] DD_{ABS} values were calculated using Eq. 6.
[b] $DD_{ABS\text{-}\%}$ values were calculated using Eq. 8.
[c] DD values were calculated using Eq. 5.
[d] $DD_{\%}$ values were calculated using Eq. 7.

Conclusions

An approach using GPR to measure sand layer volumetric water content (θ) on golf course greens was evaluated. This approach combined (1) depth (or thickness) of the sand layer measured with a steel shaft tile probe, (2) radar signal two-way travel time for the base of the sand layer obtained using a GPR system with 900 MHz antennas, and (3) an empirical equation relating porous media dielectric constant to water content. To assess accuracy, sand layer water content measured with GPR was compared to sand layer water content measured with a TDR probe. The comparison between GPR θ and TDR θ indicates that GPR can accurately measure and detect spatial and temporal changes in sand layer water content on golf course greens constructed using either the USGA or CAL Methods. In this case, GPR had an advantage over TDR, because the TDR probe only measured θ near the top of the sand layer, while GPR was able to provide a θ value averaged over the entire thickness of the sand layer. Additionally, GPR data can be acquired with much higher resolution than TDR data, and GPR techniques are not limited by disturbing the soil structure, as sometimes happens with TDR measurements.

This study indicates that sand layer θ spatial patterns are fairly consistent over time, although the overall magnitude of sand layer θ can change due to wetting and drying of the golf course green. Sand layer θ had moderate inverse correlation to surface elevation and elevation of the base of the sand layer. Other factors possibly affecting the spatial pattern of sand layer θ include spatial variability of sand layer particle size distribution and spatial variability of sand layer compaction. Data from this research also clearly demonstrated that using an average value of subsurface radar velocity can lead to large depth estimate errors, when there is substantial spatial variability in the subsurface radar velocity due to spatial variability in subsurface water content. The overall results from this investigation will be valuable to golf course architects and superintendents for quality control of green construction, repair of existing greens, and green maintenance operations.

Acknowledgments

The authors would like to express their appreciation to Todd Voss, Superintendent of the Double Eagle Golf Club (Galena, Ohio), and Justin Russell, Superintendent of the Delaware Golf Club (Delaware, Ohio), for providing access to conduct this research project at their facilities.

References

Allred, B.J., Redman, J.D., McCoy, E.L., and Taylor, R.S., 2005, Golf course applications of near-surface geophysical methods - A case study: Journal of Environmental and Engineering Geophysics, **10**(1), 1–19.

Allred, B.J., McCoy, E.L., and Redman, J.D., 2008, Ground-penetrating radar investigation of a golf course green - Computer processing and field survey set-up considerations: *in* Handbook of agricultural geophysics, Allred B.J, Daniels, J.J., and Ehsani, M.R. (ed.), CRC Press, Boca Raton, FL, 353–362.

Bohn, H.L., McNeal, B.L., and O'Connor, G.A., 1985, Soil Chemistry, 2nd Ed.: John Wiley & Sons, New York, NY.

Boniak, R., Chong, S.K., Indorante, S.J., and Doolittle, J.A., 2008, An application of ground-penetrating radar in golf course management: *in* Handbook of agricultural geophysics, Allred B.J, Daniels, J.J., and Ehsani, M.R. (ed.), CRC Press, Boca Raton, FL, 345–352.

Bradford, J.H., 2008, Measuring water content heterogeneity using multifold GPR with reflection tomography: Vadose Zone Journal, **7**, 184–193.

Conyers, L.B., 2004, Ground-penetrating radar for archaeology: AltaMira Press, Walnut Creek, CA.

da Silva, F.F., Wallach, R., Polak, A., and Chen, Y., 1998, Measuring water content of soil substitutes with time-domain reflectometry (TDR): J. Am. Hortic. Soc., **123**, 734–737.

Drungil, C.E.C., Abt, K., and Gish, T.J., 1989, Soil moisture determination in gravely soils with time domain reflectometry: Trans. ASAE, **32**, 177–180.

Farmani, M.B., Keers, H., and Kitterød, N., 2008, Time-lapse GPR tomography of unsaturated water flow in an ice-contact delta: Vadose Zone Journal, **7**, 272–283.

Freeland, R.S., Allred, B.J., and Sorochan, J.C., 2014, Profiling USGA putting greens using GPR - An as- built surveying method: Journal of Environmental and Engineering Geophysics, **19**(3), 167–174.

Galagedara, L.W., Parkin, G.W., and Redman, J.D., 2003a, An analysis of the ground-penetrating radar direct ground wave method for soil water content measurement: Hydrological Processes, **17**, 3,615–3,628.

Galagedara, L.W., Parkin, G.W., Redman, J.D. and Endres, A.L., 2003b, Assessment of soil moisture content measured by borehole GPR and TDR under transient irrigation and drainage: Journal of Environmental & Engineering Geophysics, **8**, 77–86.

Golden Software, Inc., 2002, Surfer 8 user's guide: Golden Software, Inc., Golden, CO.

Grote, K., Anger, C., Kelly, B., Hubbard, S, and Rubin, Y., 2010, Characterization of soil water content variability and soil texture using GPR groundwave techniques: Journal of Environmental and Engineering Geophysics, **15**(3), 93–110.

Grote, K., 2013, A summary of ground penetrating radar techniques for soil water content monitoring: *in* FastTIMES, **18**, No. 3, 18–29.

Huisman, J.A., Hubbard, S.S., Redman, J.D., and Annan, A.P., 2003, Measuring soil water content with ground penetrating radar - A review: Vadose Zone Journal, **2**, 476–491.

Hurdzan, M.J., 2004, Golf greens - History, design, and construction: John Wiley & Sons, Inc., Hoboken, NJ.

Hurdzan, M.J., 2006, Golf course architecture - Evolutions in design, construction, and restoration technology - 2nd ed.: John Wiley & Sons, Inc., Hoboken, NJ.

Kaiser, D.R., Reinert, D.J., Reichert, J.M. and Minella, J.P.G., 2010, Dielectric constant obtained from TDR and volumetric moisture of soils in southern Brazil: R. Bras. Ci. Solo, **34**, 649–658.

Kelleners, T.J., Seyfried, M.S., Blonquist, Jr., J.M., Bilskie, J., and Chandler, D.G., 2005, Improved interpretation of water content reflectometer measurements in soils: Soil Sci. Soc. Am. J. **69**, 1,684–1,690.

National Golf Foundation, 2013, Golf facilities in the U.S. - 2013 ed.: National Golf Foundation, Jupiter, FL.

Ohio Agricultural Research and Development Center, 2015, OARDC weather system: http://www.oardc.ohio-state.edu/newweather/.

Prettyman, G.W., and McCoy, E.L., 2003, Profile layering, root zone permeability, and slope affect on soil water content during putting green drainage: Crop Science, **43**, 985–994.

Robinson, D.A., Jones, S.B., Blonquist Jr., J.M., and Friedman, S.P., 2005, A physically derived water content/permittivity calibration model for coarse-textured, layered soils: Soil Sci. Soc. Am. J. **69**, 1,372–1,378.

Roth, C.H., Malicki, M.A., and Plagge, R., 1992, Empirical evaluation of the relationship between soil dielectric constant and volumetric water content as the basis for calibrating soil moisture measurements by TDR: European Journal of Soil Sci., **43**, 1–13.

Santamarina, J.C., and Fam, M., 1997, Dielectric permittivity of soils mixed with organic and inorganic fluids (0.02 GHz to 1.30 GHz): Journal of Environmental and Engineering Geophysics, 2, 37–51.

Schaap M.G., de Lange L., and Heimovaara T.J., 1996, TDR calibration of organic forest floor media: Soil Technology, **11**, 205–217.

Seyfried, M.S. and Murdock, M.D., 2004, Measurement of soil water content with a 50-MHz soil dielectric sensor: Soil Sci. Soc. Am. J., **68**, 394–403.

Sutinen, R., 1992, Glacial deposits, their electrical properties and surveying by image interpretation and ground penetrating radar: Bulletin 359, Geological Survey of Finland, Rovaniemi, Finland.

Take, W.A, Arnepalli, D.N., Brachman, R.W.I., and Rowe, R.K., 2007, Laboratory and field calibration of TDR probes for water content measurement: Conference Proceedings of OttawaGeo2007, Canadian Geotechnical Society and International Association of Hydrogeologists – Canadian National Chapter, 1865-1871.

Topp, G.C., Davis, J.L., and Annan, A.P., 1980, Electromagnetic determination of soil water content-Measurements in coaxial transmission lines: Water Resources Research, **16**(3), 574–582.

United States Golf Association, 2004, USGA recommendations for a method of putting green construction: United States Golf Association, Far Hills, NJ.