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Investigation of utility of Delta-T Theta Probe for obtaining surficial moisture measurements on beaches

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INVESTIGATION OF UTILITY OF DELTA-T THETA PROBE FOR OBTAINING SURFICIAL MOISTURE MEASUREMENTS ON BEACHES

A Thesis

Submitted to the Graduate Faculty of the
Louisiana State University and
Agricultural Mechanical College
in partial fulfillment of the
requirements for the degree of
Master of Science

in

Department of Geography and Anthropology

by
Phillip P. Schmutz
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ABSTRACT

Recent studies have reported on the use of a new device to measure beach 'surface' moisture content, the Delta-T Theta Probe. However, the sensor length (6.0 cm) is too long for measurement of true surface moisture conditions. This study investigated the reliability of the Theta Probe as sensor length is reduced to lengths of 1.5, 1.0, and 0.5 cm. Field investigations were conducted at sites in Texas and North Carolina, in order to evaluate the influence of differing sediment sizes on probe output. It was found that calibration R^2 values remained high and only a minimal increase in standard error occurred as the length of the sensor rod array was shortened. However, the sensitivity of the Theta Probe response to changes in moisture content was influenced by the length of the sensor rod array, weakening as sensor length was reduced. Sediment size does not influence the calibration strength or accuracy of the Theta Probe, as the R^2 values and SE values are not significantly different at the 95% confidence interval between grain sizes. Comparison of multiple calibration repetitions and different probes showed that the Theta Probe is reliable and the probe units are interchangeable.

Chapter 1

Introduction

1.1 Background

Soil moisture, in general, is important to a wide range of natural and human systems. Of special interest is the top few cm of the soil surface (Namikas and Sherman, 1995; Kaleita et al., 2006). This is because of the importance of surface water content to the near-surface energy balance (Abu-Hamdeh, 2003), climate and landscape modeling (Cosh et al., 2005), and micro and macro fauna habitat (Hayward et al., 2004; Colombini et al., 2005), etc. It can also play a significant role in aeolian geomorphology, particularly in coastal environments (Logie, 1982; Sherman et al., 1998; Davidson-Arnott et al., 2005). One of the greatest challenges in working in coastal-aeolian systems lies in the measurement of moisture content over suitable ranges of space and time (McKenna Neuman and Langston, 2006). The most common approach to measuring surface moisture content of beach sediments involves the removal of sand samples from the beach, generally through physical surface scrapings, and subsequent drying and weighing in the laboratory (e.g., Sarre, 1988; Jackson and Nordstrom, 1998; Wiggs et al., 2004). This methodology has significant limitations, in that it is both destructive and time consuming (Atherton et al., 2001). These limitations have long prevented collection of surface moisture data over large enough and at frequent enough intervals to allow for establishment of spatial and temporal patterns. Thus, although it is known that moisture content exerts a strong control over aeolian transport, it has not been possible to apply this knowledge in the context of ‘real’ world beaches.

Recently, Atherton et al. (2001) and Yang and Davidson-Arnott (2005) reported on the use of a new instrument to measure beach moisture content, the Delta-T Theta Probe (Figure

1.1). Atherton et al. (2001) noted that it allows frequent, non-destructive measurements of moisture content to be made. Furthermore, individual measurements require only a few seconds so that coverage of large spatial areas is feasible. Yang and Davidson-Arnott (2005) also showed that the probe can be modified to provide measurements from a relatively shallow surface layer. These studies demonstrate that the Delta-T Theta Probe has great potential for providing reliable measurements of the moisture content of beaches and allows for the mapping and modeling of this important influence on aeolian transport.

Figure 1.1: Delta-T Theta Probe soil moisture sensor
Photo by: Phillip Schmutz

1.2 Problem Context

A key weakness concerning the Delta-T Theta Probe is that the sensor rod array, at a length of 6.0 cm, is too long to measure 'surface' moisture conditions that influence aeolian transport. To deal with this problem Yang and Davidson-Arnott (2005) used a 4 cm thick cube of dielectric foam leavening only 2 cm of the sensor rod array exposed. The authors chose a 2 cm sensor length as a compromise between restricting measurements to as close to the surface as possible and minimizing the decrease in accuracy and precision resulting from a shortened array. Results of their study do not document a significant decrease in either accuracy or precision as probe length is decreased. Laboratory and field calibrations at the 2 cm sensor rod length produce acceptable R^2 values.

Yang and Davidson-Arnott (2005) found that the Delta-T Theta Probe is very reliable to a measurement depth of 2 cm. However, it is suggested within the literature that moisture measurement sample depths should ideally be restricted to a few millimeters (Sarre, 1988; Namikas and Sherman, 1995). There are no studies available to date that document the reliability of the Delta-T Theta Probe at measurement depths shallower than 2 cm. This study will shed light on this problem by investigating the performance of the Delta-T Theta Probe as the sensor rod array is decreased to lengths of 1.5, 1.0, and 0.5 cm.

1.3 Purpose of Study

This study assesses the reliability of the Delta-T Theta Probe in determining shallow depth surface moisture content on beaches. To accomplish this task, this study will address the following objectives regarding this device.

1) How do the calibrations, and its reliability, vary as sensor rod length is decreased?
2) How do the calibrations, and its reliability, vary between sediment grain sizes?
3) What is the reliability of the Delta-T Theta Probe to sample multiple moisture content measurements within a single probe and between different probes?
4) Is there any improvement in accuracy and strength of the calibrations by using a third-order polynomial relationship over a linear relationship?
5) How reliable are the manufacturer's specified calibration approaches?

The Delta-T Theta Probe may provide the solution that allows workers to monitor spatial and temporal patterns of surface moisture content at shallow depths on beaches and begin to develop models of this variability. Results of this project will provide a clearer understanding of the capabilities of the Delta-T Theta Probe for use in determining surface moisture contents.

Chapter 2

Literature Review

Several important techniques regarding measurement of surface moisture content are discussed in this chapter. The ‘traditional’, ‘indirect’, and ‘electronic’ measurement techniques will be discussed, along with their associated weaknesses for collection of surface moisture content associated with coastal-aeolian sediment transport. This chapter will conclude with a description of the Delta-T Theta Probe.

2.1 Moisture Measurement Techniques

When conducting surface moisture research associated with aeolian transport, ideally, a measurement technique should be light weight and portable to allow for measurement over large spatial areas. It should also allow for frequent or continuous measurements in the same place with only small expenditure of time, allow for multiple measurements in the same place with minimal disturbance to measurement location, conduct measurements at shallow depths (less than 2 cm) and be durable enough to undergo standard wear and tear.

2.1.1 Traditional Techniques

2.1.1.1 Physical Sampling

A traditional approach for collection of surface moisture content involves the removal of a known volume of the soil sample, generally through physical surface scrapings. The sample is then weighed, oven-dried, and re-weighed to determine water content either volumetrically (θ_v) or gravimetrically (θ_g) (Topp and Davis, 1984; Dean et al., 1987; Sarre, 1988; Namikas and Sherman, 1995; Jackson and Nordstrom, 1997; Tsegaye et al., 2004; Yang and Davidson-Arnott, 2005). Water content is calculated as:

$$\theta_v = \frac{(w_s - w_d)/\rho_w}{w_d/\rho_s} \tag{2.1}$$

or

$$\theta_g = \frac{(w_s - w_d)}{w_d} \tag{2.2}$$

where w_s is the total sample weight, w_d is the dry sample weight, ρ_d is the water density, and ρ_s is the sediment density.

Despite its wide-spread use, this methodology has a number of serious limitations. For example, the destructive nature of the methodology excludes repeat measurements at the same locations. The technique is also time consuming both in the field and in subsequent laboratory analysis, which limits the number of samples that can be used to characterize the relationship. These limitations have prevented the establishment of spatial and temporal pattern analysis of surface moisture (Dean et al., 1987; Atherton et al., 2001; Tsegaye et al., 2004; Kaleita et al., 2005a; Yang and Davidson-Arnott, 2005).

2.1.1.2 Tensiometers

A second traditional technique for the measurement of moisture content involves the use of tensiometers. Tensiometers measure the hydrostatic pressure of the soil through the use of a porous membrane connected by a tube filled with water to a manometer, which may be a simple water- or mercury-filled U-tube, a vacuum gauge, or an electrical transducer. As the porous membrane is placed within the soil, the bulk water inside the tube comes into hydraulic contact and tends to equilibrate with the surrounding soil water conditions through the pores in the membrane. Depending upon the initial hydrostatic pressure of the soil water at the location of measurement, the tensiometer will record either an increase or decrease in the hydrostatic pressure of the device (Richards, 1942; Hillel, 1971; Mullins et al., 1986; Orr, 2001, Take and Bolton, 2003).

Because tensiometers do not directly measure the moisture content of the soil, they must be calibrated to identify the relationship between soil moisture pressure and soil moisture content. Hillel (1971, 63) pointed out that “the amount of soil moisture content at relatively low soil moisture pressure values depends primarily upon the capillary effect and the pore-size distribution, and hence is strongly affected by the structure of the soil. On the other hand, the amount of soil moisture content at higher soil moisture pressure values is due to adsorption and is thus influenced less by the structure and more by the texture of the soil material.” This indicates that the soil structure and soil texture notably influence the calibration relationship (Figure 2.1).

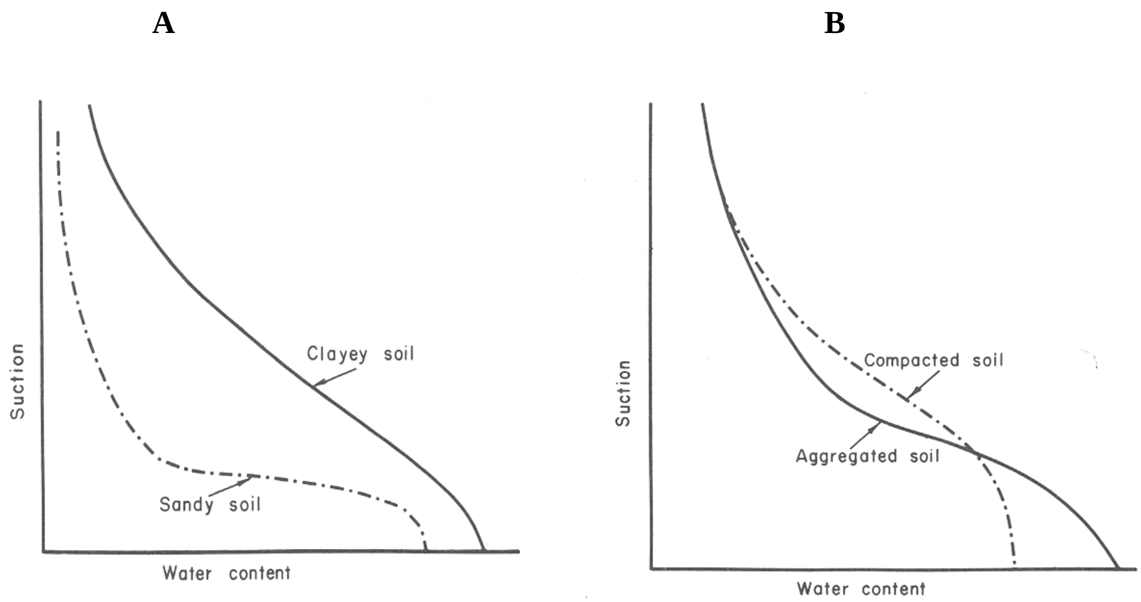


Figure 2.1: (A) Influence of soil structure on calibration relationship. (B) Influence of soil texture on calibration relationship.
Source: Hillel, 1971

A major strength of tensiometers is that they provide reliable data of the *in situ* state of moisture conditions over time. However, the technique has a serious limitation. The equipment involved is not conducive to being highly portable; therefore, tensiometers are generally utilized as long term, permanent to semi-permanent monitoring sites. This diminishes its use for measurement over large spatial scales unless multiple devices are implemented, which increases the cost of the research.

2.1.2 Indirect Techniques

2.1.2.1 Remote Sensing

Remote sensing measurements of soil moisture record the amount of radiation in a given wavelength reflected off of or emitted from the surface to the sensor (Kaleita et al., 2005b). The two most widely used remotes sensing techniques to measure soil moisture are microwave sensors, and visible and near-infrared sensors (VIS-NIR) (Jackson el al., 1996; Muller and Decamps, 2001; Kaleita et al., 2005b).

There are significant advantages in using microwave or VIS-NIR sensors for agricultural applications; however; these remote sensing techniques are not practical for the measurement of surface moisture on beaches. Spatial resolution is very low, having at best a resolution on the order of tens of meters (Jackson et al.; 1996; Muller and Decamps, 2001). Additionally, these techniques provide a very low temporal scale (Muller and Decamps, 2001).

2.1.2.2 Digital Photography

Recently McKenna Neuman and Langston (2003, 2006) have reported on the technique of using digital photography to measure surface moisture content. The theory behind the methodology is based on the principle that the pixel luminosity from a grey scale digital image is a reflection of moisture content of the soil. To determine pixel luminosity or brightness (B), the image must be converted to an 8-bit grayscale image composed of 256 shades of grey, which range in values from 0 (black) to 256 (white). The image is then processed to determine the number pixels associated with each of the 256 brightness levels (McKenna Neuman and

Langston, 2003; 2006).

Calibrations between surface brightness and surface moisture indicated strong relationships with R^2 values above 0.80 for the laboratory and field data sets, and an R^2 value of 0.88 for the bulk calibration combining all laboratory and field data sets (McKenna Neuman and Langston, 2003; 2006). These results suggest that that the pixel luminosity or surface brightness (B), of a digital photograph, is strongly correlated with surface moisture content.

Overall, use of digital photography to measure surface moisture appears to be an extremely promising technique. A few major advantages in utilizing digital photography to measure moisture content is that the methodology is relatively simple to execute, allows for measurement of the uppermost grains of the soil surface, and multiple measurements in the same location with minimal disturbance to that measurement location. Additionally, the affordability and easy portability of digital cameras allows for measurement over large spatial areas utilizing either one or multiple devices. There are, however; a few limitations to the technique. The reflectance of a soil surface is often affected by particle size distribution, mineral composition, color of the soil elements, as well as, roughness of the soil surface, which can cause shadows (McKenna Neuman and Langston, 2003; Kaleita et al. 2005b; McKenna Neuman and Langston, 2006).

2.1.3 Electronic Sensor Techniques

Advances in obtaining surface water content through electronic sensors over the past half-century have been spent on the development of several dielectric based surface moisture techniques such as time-domain reflectometry (TDR) (Topp et al., 1980; Topp and Davis, 1984; Roth et al., 1992; Whalley, 1993) capacitance (Dean et al., 1987; Paltineanu and Starr, 1997; Fares and Polyakov, 2006) and impedance (Gaskin and Miller, 1996; Miller and Gaskin, 1998;

Cosh et al., 2005; Kaleita et al., 2005a).

Dielectric-based soil water monitoring techniques seek to identify the correlation between the apparent dielectric contestant (*K*) of the soil-water-air matrix and soil water content (θ). The dielectric constant (*K*) of a material arises from the polarization or electric dipole moment within the material as an external electrical field is applied. In nature, the dielectric constant of free water has a particularly high permanent electric dipole moment, resulting in a substantially large dielectric constant (~ 80) compared to both soil (~5 for pure mineral soils) and air (~1), and thus dominates the dielectric permittivity of the soil-water-air matrix (Dean, et al., 1987; Gaskin and Miller, 1996; Paltineanu and Starr, 1997; Robinson et al., 1999; Fares and Polyakov, 2006). From an electromagnetic standpoint, a soil is a complex mixture that can be represented as a four-component dielectric mixture of air, bulk soil density, bound water, and free water (Dean, et al., 1987; Paltineanu and Starr, 1997; Topp et al. 1980).

Given that electromagnetic sensors measure the dielectric properties of the soil-water-air matrix the relationship between this parameter and soil water content must be accurately known to achieve a suitable calibration. Whalley (1993) and Gaskin and Miller (1996) describe a simple linear relationship between the square root of the dielectric constant of the soil medium (*K*) and water content (θ) as:

$$\theta = \frac{\sqrt{K} - a_0}{a_1} \tag{2.3}$$

where a_1 and a_0 are coefficients representative of the soil structure and found to have typical values of 8.1 and 1.6 for mineral soils and 7.7 and 1.3 for organic soils, respectively. Other studies indicate that the output relationship between the dielectric contestant (*K*) and soil water content (θ) is better represented in a non-linear third-order polynomial power function (Topp et al.; 1980; Paltineanu and Starr, 1997; Fares and Polyakov, 2006). The non-linearity of the relationship can be attributed to bound water, which exhibits a dissimilar behavior under the influence of an electromagnetic field than that of free water, since it has a dielectric constant of 4 or 1/20 that of free water (Paltineanu and Starr, 1997).

2.1.3.1 Time-Domain Reflectometry (TDR)

Time-Domain Reflectometry (TDR) is based on the fact that the speed of propagation of microwave pulses in conducting cables inserted in the soil is very sensitive to the soil water content (Souza and Matsura, 2003). In TDR, the propagation velocity of a high-frequency electromagnetic signal is determined by:

$$v = \frac{c}{\sqrt{K}} \tag{2.4}$$

where v is the propagation velocity along conducting cables, c is the propagation velocity of electrical signals in vacuum/free space (3×10^8 m s^{-1}), and K is the measured dielectric constant. In application, to determine the dielectric constant (K) the velocity (v) of the two-way travel must be calculated as:

$$v = \frac{2L}{t} \tag{2.5}$$

where L is the length of the transmission line or wave guide, and t is the two-way travel time. Combining the mathematical equations 2.4 and 2.5, the dielectric constant of the measured medium can be calculated by:

$$K = \left(\frac{ct}{2L}\right)^2 \tag{2.6}$$

TDR is the most commonly used electrical sensor technique, primarily for agricultural practices. Despite its wide-spread use, the technique has some major limitations. The TDR methodology requires extremely long probe lengths (often in excess of 0.5 m) to determine the reflection of electromagnetic waves or propagation velocity (Souza and Matsura, 2003). Probes of these lengths are often difficult to insert into the soil, diminishing the repeatability of the probe to measure multiple samples at the same location with minimal disturbance to the soil. Second, probes of these lengths far exceed the measurement of shallow depths associated with aeolian transport processes. In addition, TDR sensors are extremely expensive (Gaskin and Miller, 1996). The expense to employ multiple TDR sensors reduces the ability of measurement over large spatial areas.

2.1.3.2 Capacitance Technique

Capacitance is defined as the ability of two conductors to store a charge when a voltage is applied across them (Fares and Polyakov, 2006). In essence, capacitance sensors measure an output oscillation frequency (*F*), which is a function of the circuitry inductance (*L*) sensors and electrode-soil capacitance (*C*) (Equation 2.7) (Dean, et al., 1987; Paltineanu and Star, 1997; Robinson et al., 1999; Fares and Polyakov, 2006).

$$F = \frac{1}{2\pi\sqrt{LC}} \tag{2.7}$$

The relationship between the capacitance and the dielectric constant of the medium (*K*) is:

$$C = K_o K g \tag{2.8}$$

where K_o is the dielectric constant in vacuum (8.5 pFm-1), and g is the geometric configuration of the circuitry sensors.

There are several disadvantages to capacitance sensors. Capacitance sensors require the installation of PVC access tubes (Gaskin and Miller, 1996), which diminishes its use for measurement over large spatial scales unless multiple devices are implemented. The presence of air gaps or changes in pressure within the PVC access tube can create anomalous results (Bell et al., 1987; Paltineanu and Star, 1997). Furthermore, capacitance sensors are highly sensitive to soil temperature and salinity (Fares and Polyakov, 2006).

2.1.3.3 Impedance Technique

Initial research into the potential uses of the impedance technique to determine soil water content was conducted by Gaskin and Miller (1996) and Miller and Gaskin (1998). The impedance (Z) of a coaxial transmission line is dependent on its physical dimensions and the dielectric constant of the soil medium.

$$Z = \frac{60}{\sqrt{K}} \ln\left(\frac{r_2}{r_1}\right) \tag{2.10}$$

where r_1 is the radius of the inner sensor rod, r_2 is the radius of the shield sensor rod array and K is the dielectric constant of the soil medium (Gaskin and Miller, 1996; Miller and Gaskin, 1998). Rearranging equation 2.10, the dielectric constant of the soil medium (K) can be determined as:

$$K = \left(\frac{60\ \ln\frac{r_2}{r_1}}{Z}\right)^2 \tag{2.11}$$

The probe generates a sinusoidal oscillator signal, which is propagated along a specifically designed transmission line into an array of sensor rods. If the impedance of the sensor rod array differs from that of the transmission line, a proportion of the incident signal, termed the reflection coefficient (ρ), is reflected back along the line towards the signal source:

$$\rho = \frac{Z_p - Z_l}{Z_p + Z_l} \tag{2.12}$$

where Z_p is the sensor rods impedance and Z_l *is* the impedance of the transmission line. This reflected component (ρ) interferes with the incident signal causing a voltage standing wave to be set up on the transmission line, i.e. a variation of voltage amplitude along the length of the line (Gaskin and Miller, 1996; Miller and Gaskin, 1998). It is the difference in this voltage amplitude at the transmission line/sensor rod junction (Eq. 2.13), which determines the probe's relative impedance; hence the dielectric constant and thus a measurement of soil water content.

$$V_j - V_o = 2a\rho = 2a\left(\frac{Z_p - Z_l}{Z_p + Z_l}\right) = Z \tag{2.13}$$

where a is the voltage amplitude of the oscillator output, V_j is the peak voltage at the junction [$V_j = a(1+\rho)$], and V_o the peak voltage at the start of the transmission line [$V_o = a(1-\rho)$].

2.2 Delta-T Theta Probe

A commonly used impedance sensor is the Delta-T Theta Probe, type ML2x (Delta-T Devices, Cambridge, England) (Delta-T Devices, 1999; Atherton et al., 2001; Tsegaye et al., 2004; Cosh et al, 2005; Kaleita et al., 2005a; Yang and Davidson-Arnott, 2005). The Theta Probe generates a 100 MHz sinusoidal signal and outputs the measured impedance of the sampling medium as an analogue DC voltage between 0 and 1 V. The 100 MHz signal frequency was chosen to minimize the effect of ionic conductivity (Miller and Gaskin, 1998). The soil sampling volume consists of a cylindrical four signal rod array roughly 4.0 cm in diameter and 6.0 cm long surrounding a center signal rod (Miller and Gaskin, 1998; Delta-T Devices, Ltd., 1999).

An empirical approach must be taken to calibrate the device, due to the difficulties in modeling the theoretical impedance response (Gaskin and Miller, 1996). Miller and Gaskin (1996) determined that the relationship between Theta Probe output (V) and the square root of the dielectric constant of the medium ($\sqrt{K}$) can be described either by a linear relationship:

$$\sqrt{K} = 4.44V + 1.10 \tag{2.14}$$

or by the more precise third order polynomial:

$$\sqrt{K} = 4.70V^3 - 6.40V^2 + 6.40V + 1.07 \tag{2.15}$$

As previously mentioned Whalley (1993) and Gaskin and Miller (1996) describe in equation 2.3 a simple linear relationship between the square root of the dielectric constant of the soil medium (K) and water content (θ). By substituting equations 2.14 and 2.15 into equation 2.3, Delta-T Devices, Ltd. (1999) established the relationship between water content (θ) and

Theta Probe voltage output (*V*) to be:

$$\theta = \frac{[4.44V+1.10]-a_0}{a_1} \tag{2.16}$$

and

$$\theta = \frac{[4.70V^3-6.40V^2+6.40V+1.071.07+6.4V]-a_0}{a_1} \tag{2.17}$$

where a_0 and a_1 are 1.6 and 8.4 for mineral soil and 1.3 and 7.7 for organic soil, respectively. The manufacturers rated accuracy for this generalized calibration is ±5.0 % volumetric moisture content (Delta-T Devices, Ltd., 1999).

To minimize the error of the generalized calibration the manufacturer recommends the using a site-specific calibration. By executing a site specific calibration, the rated accuracy increases to ±1.0% volumetric moisture content. To perform a soil-specific calibration, the manufacturer recommends a two-point technique that requires a voltage output reading for the initial moist sample, which is oven-dried and then a second voltage output reading is taken for the dry sample. Calibration coefficients a_1 and a_0 are then calculated from the wet and dry voltage output readings (Delta-T Devices, Ltd., 1999).

Chapter 3

Study Site and Methods

The first section of this chapter contains a brief description of each study site. The following two sections present a description of the methods employed in the field and subsequent lab and statistical analysis techniques.

3.1 Study Sites

Field investigations for this study were conducted at sites in Padre Island National Seashore, Texas (August 2-5, 2006), and Kill Devil Hills, North Carolina (December 27-29, 2006). These research sites were selected to provide contrasting natural sediment sizes, which will enhance the applicability of the results of this study.

3.1.1 Padre Island National Seashore, Texas (PINS)

Padre Island National Seashore occupies a large barrier island that extends 182 kilometers along the southeastern shore of Texas (Figure 3.1). The modal beach state is dissipative with a three-bar, longshore bar and trough morphology. The beach is roughly 60-70 meters wide and is backed by a near-continuous foredune (Weise and White, 1980). Sediment is very-well sorted and consists of fine to very-fine quartz grains with a mean diameter of 0.15mm (determined via sieve analysis). Tides within the region are microtidal, with a range of about 0.8 meters and a diurnal cycle (Weise and White, 1980; NOAA, 2007).

The regional climate is generally characterized by subtropical and semi-arid conditions with an average summer temperature of 35°C, an average winter temperature of 10°C, and a mean annual rainfall of 76 cm (Weise and White, 1980; NCDC, 2007). Prevailing winds are from the southeast during summer. The dominant wind direction shifts to a northerly direction during the winter due to cold polar fronts (Weise and White, 1980).

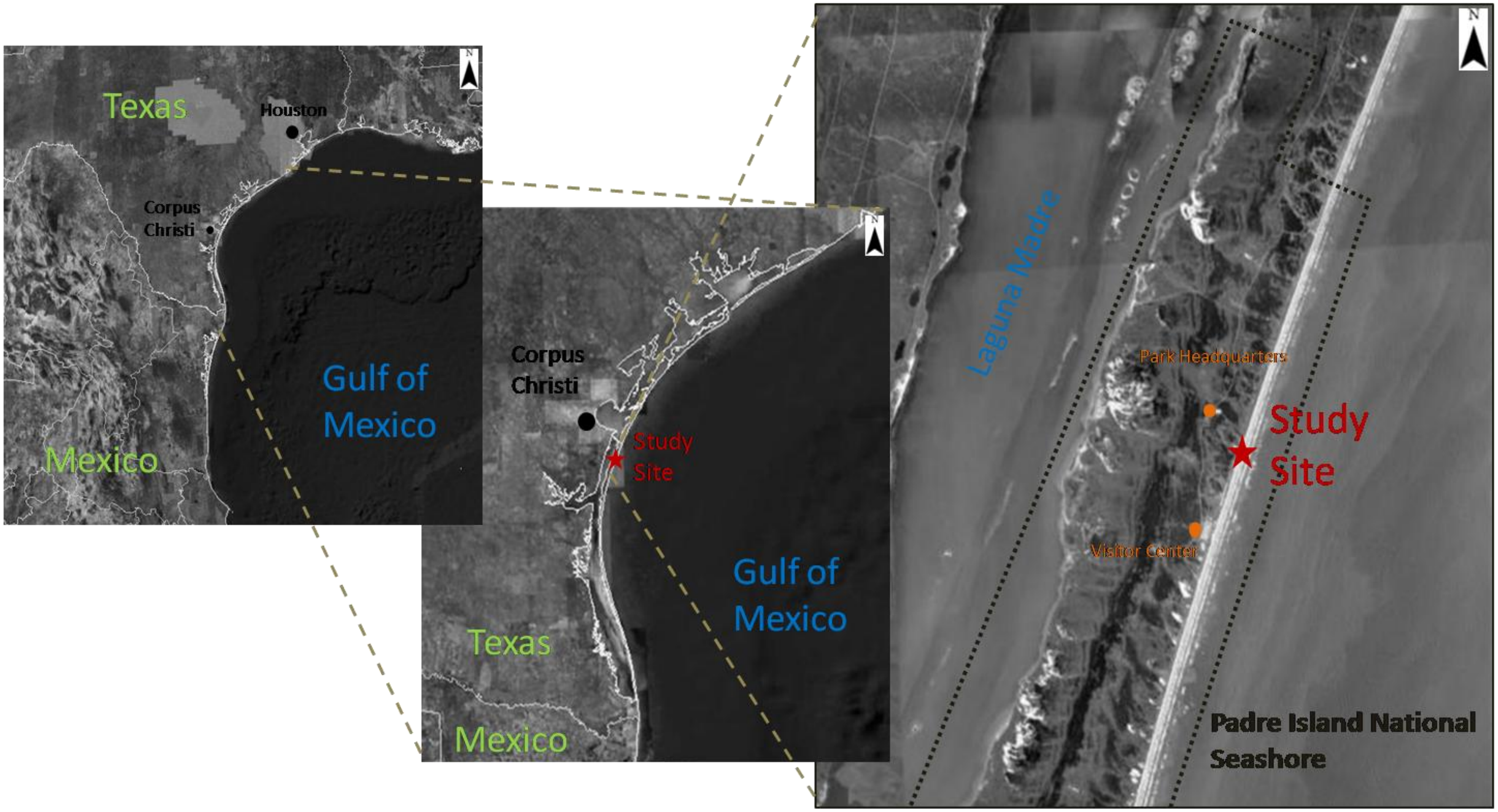


Figure 3.1: Location of study site at Padre Island National Seashore, Texas.

3.1.2 Kill Devil Hills, North Carolina (KDH)

The town of Kill Devil Hills lies along the northern portion of the North Carolina Outer Banks barrier islands (Figure 3.2). The modal beach state is intermediate, with a transverse bar and beach morphology. The beach is roughly 30-40 meters wide and is backed by a consistent 3-4 m high foredune. Sediment consists primarily of medium quartz grains with a mean diameter of 0.37mm (determined via sieve analysis); along with a small but varying percentage of shells and shell fragments predominantly located between the high and low tide lines. Tides within the region are microtidal with a range of roughly 0.75 meters around MSL and are dominated by a semidiurnal cycle (U.S. Army Corps of Engineers, 2007; NOAA, 2007).

The regional climate is generally characterized by an average summer temperature of 25°C, with an average winter temperature of 10°C, and a mean annual rainfall of about 140 cm (NCDC, 2007). Prevailing winds fluctuate predominantly blowing from the southwest or northeast throughout the year (U.S. Army Corps of Engineers, 2007).

3.2 Field Methods

To address the associated research questions regarding the Delta-T Theta Probe a total of four experimental runs were conducted at four sensor lengths using two different probes. Three experimental runs were conducted using probe A and one experimental run was conducted using probe B. The utilization of multiple runs with a single probe provides an assessment of the repeatability of the Theta Probe. Additionally, the employment of two probes provides an assessment of interchangeability between different probes. Furthermore, to evaluate the influence of the length of the sensor rod array, the sensor rods were inserted through various thicknesses of dielectric foam blocks to refine sensor rod length from the manufacturer supplied 6.0 cm to lengths of 1.5 cm, 1.0 cm, and 0.5 cm (Figure 3.3).

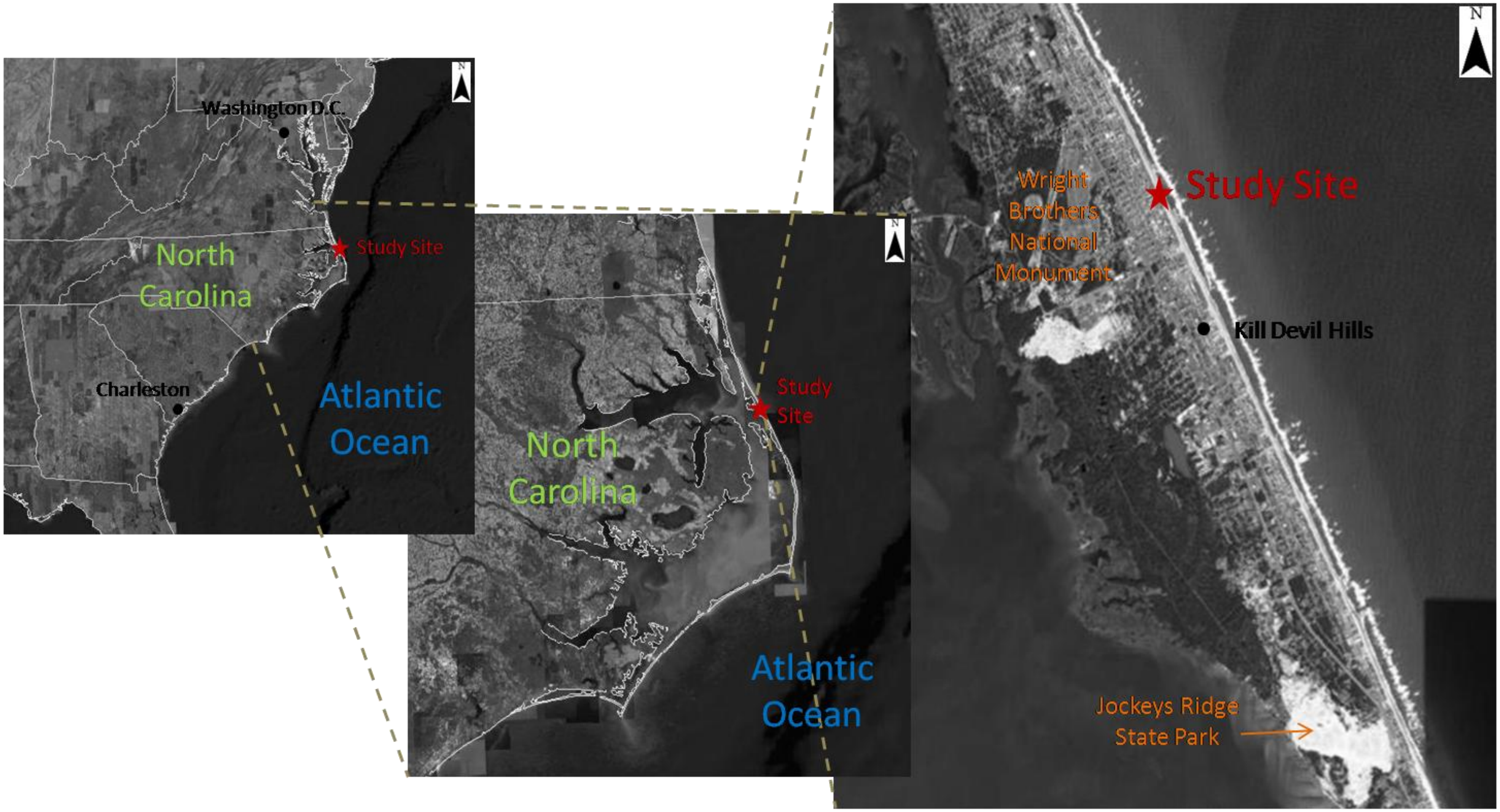


Figure 3.2: Location of study site at Kill Devil Hills, North Carolina.

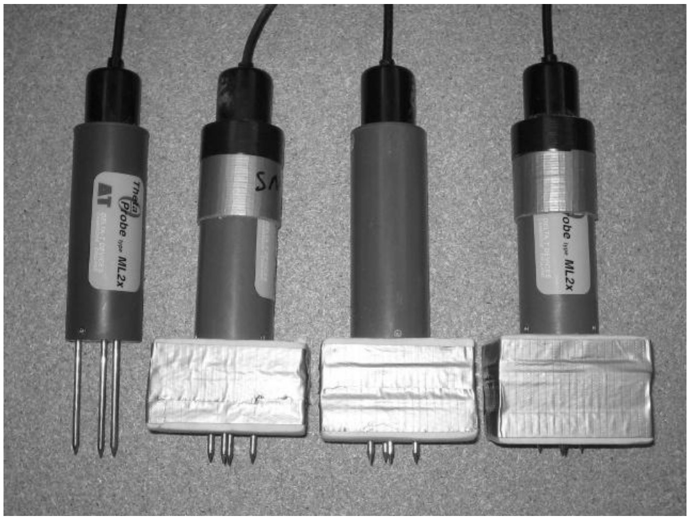


Figure 3.3: Delta-T Theta Probe inserted through dielectric foam blocks illustrating changes in sensor rod length from the manufacturer supplied 6.0 centimeters to lengths of 1.5, 1.0 and 0.5 centimeters.
Photo by: Phillip Schmutz

3.2.1 Experimental Runs

An individual experimental run consisted of a total of 20 field moisture measurement sediment samples (Kaleita et al., 2005a). The individual field sediment samples were collected by inserting the probes into the bead of the sediment and recording the voltage output using an HH2 moisture meter (Delta-T Devices, Cambridge, United Kingdom) (Delta-T Devices, 2005). Immediately following the voltage output reading a cylindrical tube (Figure 3.4) was inserted into the bead at the exact measurement location to the depth of the sensor length, and the actual sediment measured by the probe was collected. The sediment sample was then bagged, sealed, labeled, and then brought to the laboratory to determine ‘true’ moisture content via standard methods.

Figure 3.4: Cylindrical tube utilized to collect field moisture measurement samples. Rings on the tube indicate depth of measurement collection.
Photo by: Phillip Schmutz

3.3 Lab Analysis

3.3.1 Surface Moisture Content

Surface sediment sample moisture content was determined using the common standard gravimetric moisture content calculation method, as outlined by Hillel (1971) and Hanks (1992):

$$w = \frac{(w_s - w_d)}{w_d} \tag{3.1}$$

where moisture content, w, is expressed as a percent by weight of a sediment sample, and w_s and w_d are the initial sample weight and the dry sample weight, respectively. Sediment sample moisture contents were determined by weighing the initial sample (w_s) to a precision of a 0.001g, drying it in an oven at 65°C for 36 hours and re-weighing it to determine the dry sample weight (w_d).

3.3.2 Calibration

For each individual experimental run, Theta Probe voltage outputs are plotted against the gravimetric moisture contents. The relationship between voltage output and the gravimetric moisture content was described using both linear and third-order polynomial regressions. Both linear and third-order regressions were employed because the literature utilizes both regression functions for calibration relationships. In addition, a linear regression analysis was employed to describe the calibration relationships for moisture contents less than 10% (gravimetric) (Atherton et al., 2001; Yang and Davidson-Arnott 2005).

R^2 values, which represent the percentage of the total variance in moisture contents that is explained by the voltage outputs, were used to evaluate the relative strength of the calibration relationships. Higher R^2 values indicate a stronger relationship between the variables.

3.3.3 Standard Error (SE)

To further assess the reliability of the calibration relationships for the Delta-T Theta Probe, the standard error (SE) was determined for each calibration relationship. SE, which provides an evaluation of the accuracy of the probe, is calculated as:

$$SE = \sqrt{\frac{1}{n-2}\sum\left(\theta_{measured} - \theta_{predicted}\right)^2} \qquad (3.2)$$

where $\theta_{measured}$ is the laboratory determined gravimetric moisture content from a field moisture sediment sample, $\theta_{predicted}$ is the gravimetric moisture content predicted for that sediment sample based on the associated voltage output and the calibration equation, and n is the total number of samples (Harnett, 1975).

3.3.4 Analysis of Variance (ANOVA)

A total of four one-way analysis of variance (ANOVA) tests were utilized in this study to examine if sediment grain size has any influence on the R^2 values, SE values and calibration slopes of the relationships. First, an analysis of variance test was conducted on both the R^2 and SE values from the calibration relationships for the full moisture range on each of the four sensor lengths. These ANOVA tests were employed to determine if grain size has any influence on the strength and accuracy of the relationship. A second analysis of variance test was conducted on the R^2 values from the calibrations for moisture contents less than 10% (gravimetric) for all four sensor lengths. Again this ANOVA test was employed to determine the influence of grain size on the strength of the calibration relationship. Finally, an analysis of variance test was conducted on the calibration slopes of all four sensor lengths from the calibrations for moisture contents less than 10% (gravimetric). This ANOVA test was utilized to determine the influence that sediment grain size has on the probe's sensitivity to measure moisture content.

Chapter 4

Evaluation of Delta-T Theta Probe

This chapter will discuss the utility of the Delta-T Theta Probe in context of the full moisture range across the beach surface. First, an examination of differences between third-order polynomial and linear calibration relationships will be addressed. Second, the influence of sensor length will be evaluated, followed by an evaluation of the influence of sediment size on the calibration relationships. The final two sections of the chapter will assess the repeatability and interchangeability of the Delta-T Theta Probes.

4.1 Linear versus Third-order Polynomial Calibration Relationship

In the literature, both linear and third-order polynomial functions have been used for calibration relationships (Topp et al.; 1980; Whalley, 1993; Gaskin and Miller, 1996; Paltineanu and Starr, 1997; Atherton et al., 2001; Fares and Polyakov, 2006). This section is intended to determine whether a linear or third-order regression analysis produces a higher level of reliability in the calibrations of the Theta Probe.

Figures 4.1 and 4.2 illustrate the linear and third-order calibration relationships for each sensor length at the PINS study site and figures 4.3 and 4.4 illustrate the linear and third-order calibration relationships for each sensor length at the KDH study site. Visually, there is very minimal difference in the calibration relationships between the linear and third-order relationships at the 6.0 and 1.5 cm sensor lengths for both study sites. The overall slopes of the calibration relationships between the linear and third-order relationships are very similar. This indicates that the regression analysis function employed does not alter the associated sensitivity of the probe, as the slope of the relationship reflects the sensitivity of the probe’s response to moisture levels. There are, however; vast differences between the linear and third-order

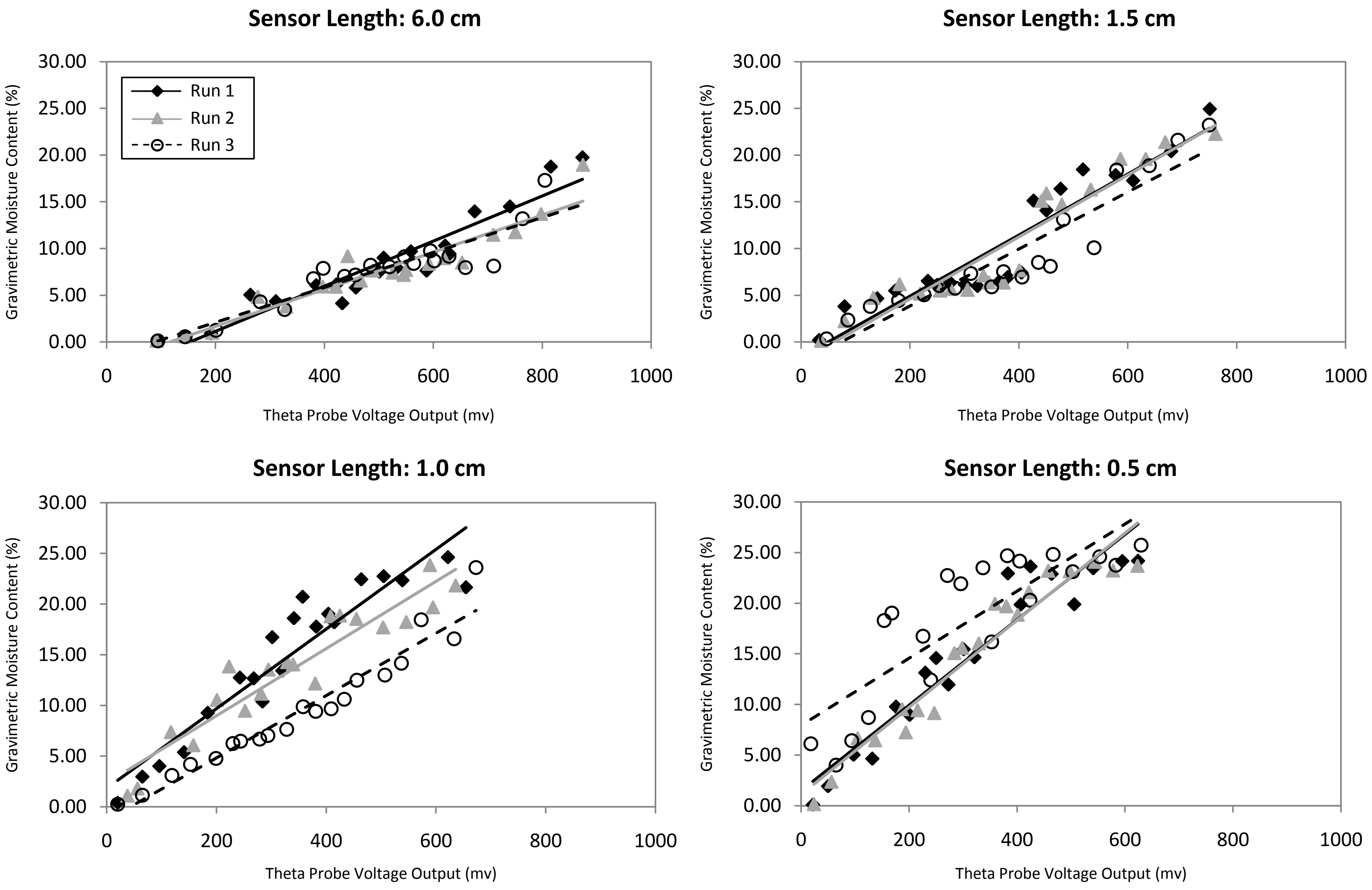


Figure 4.1: Linear calibration relationships at sensor rod lengths 6.0, 1.5, 1.0 and 0.5 cm for Padre Island National Seashore, Texas.

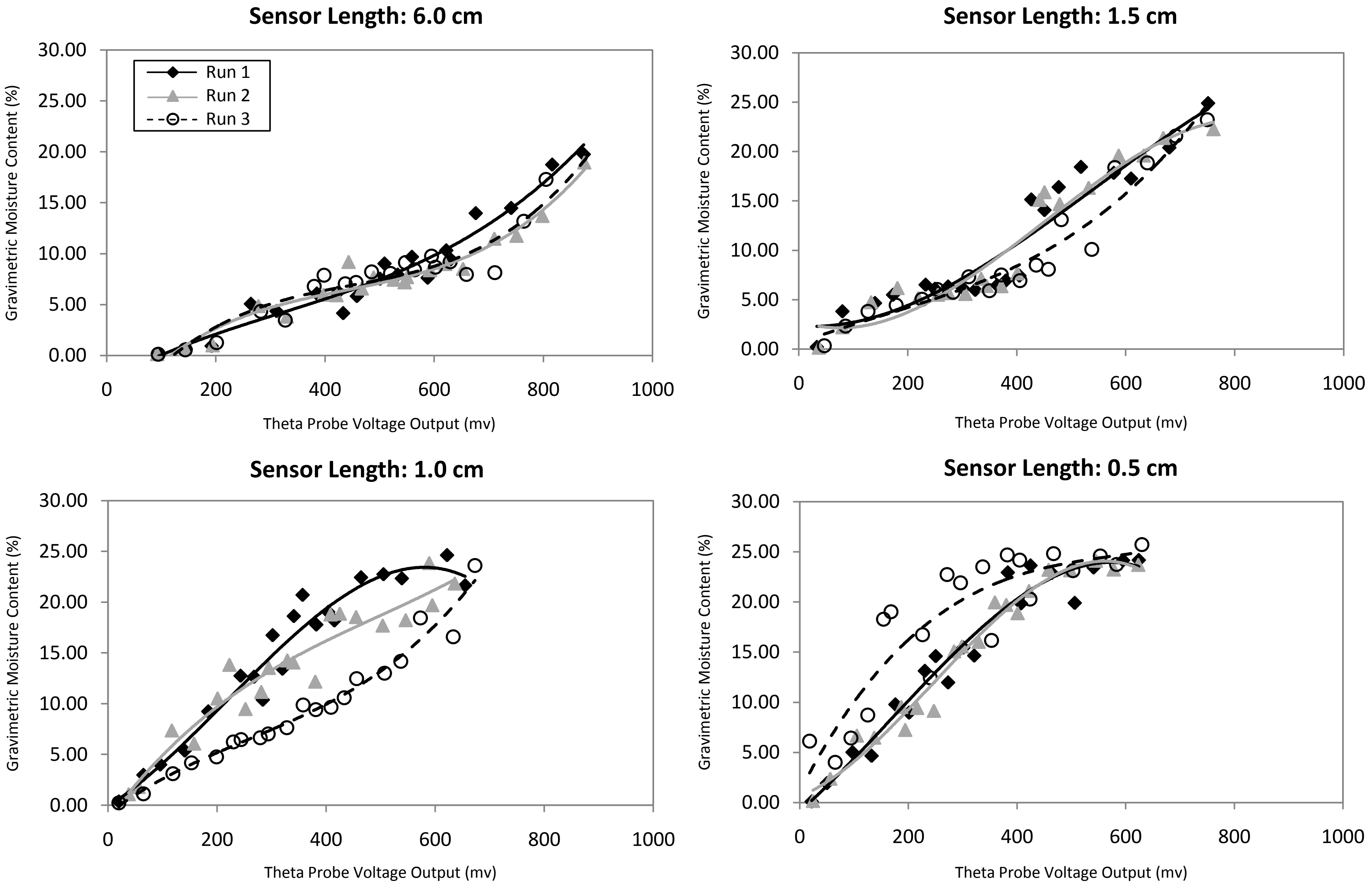


Figure 4.2: Third-order polynomial calibration relationships at sensor rod lengths 6.0, 1.5, 1.0 and 0.5 cm for Padre Island National Seashore, Texas.

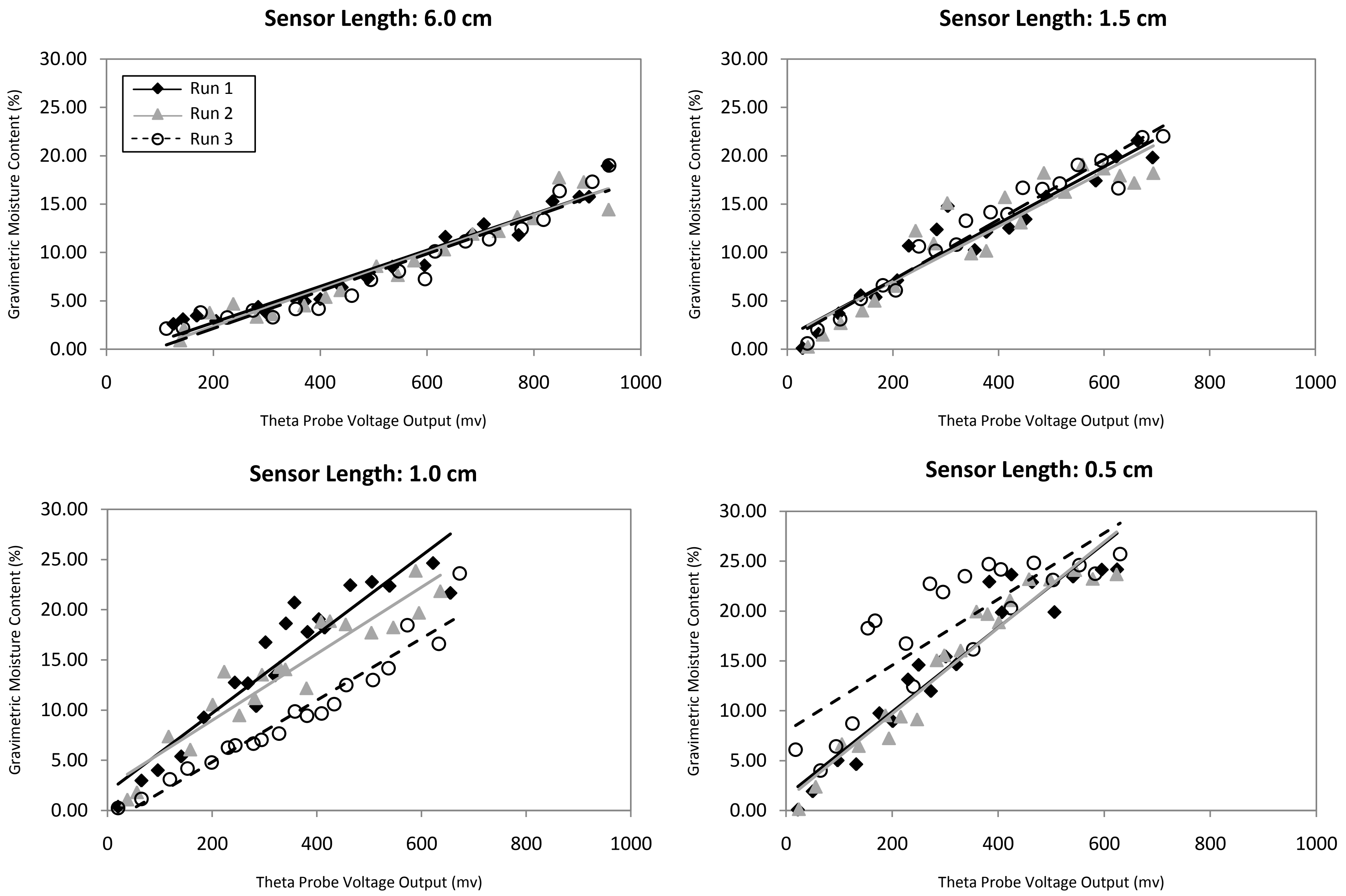


Figure 4.3: Linear calibration relationships at sensor lengths 6.0, 1.5, 1.0 and 0.5 cm for Kill Devil Hills, North Carolina.

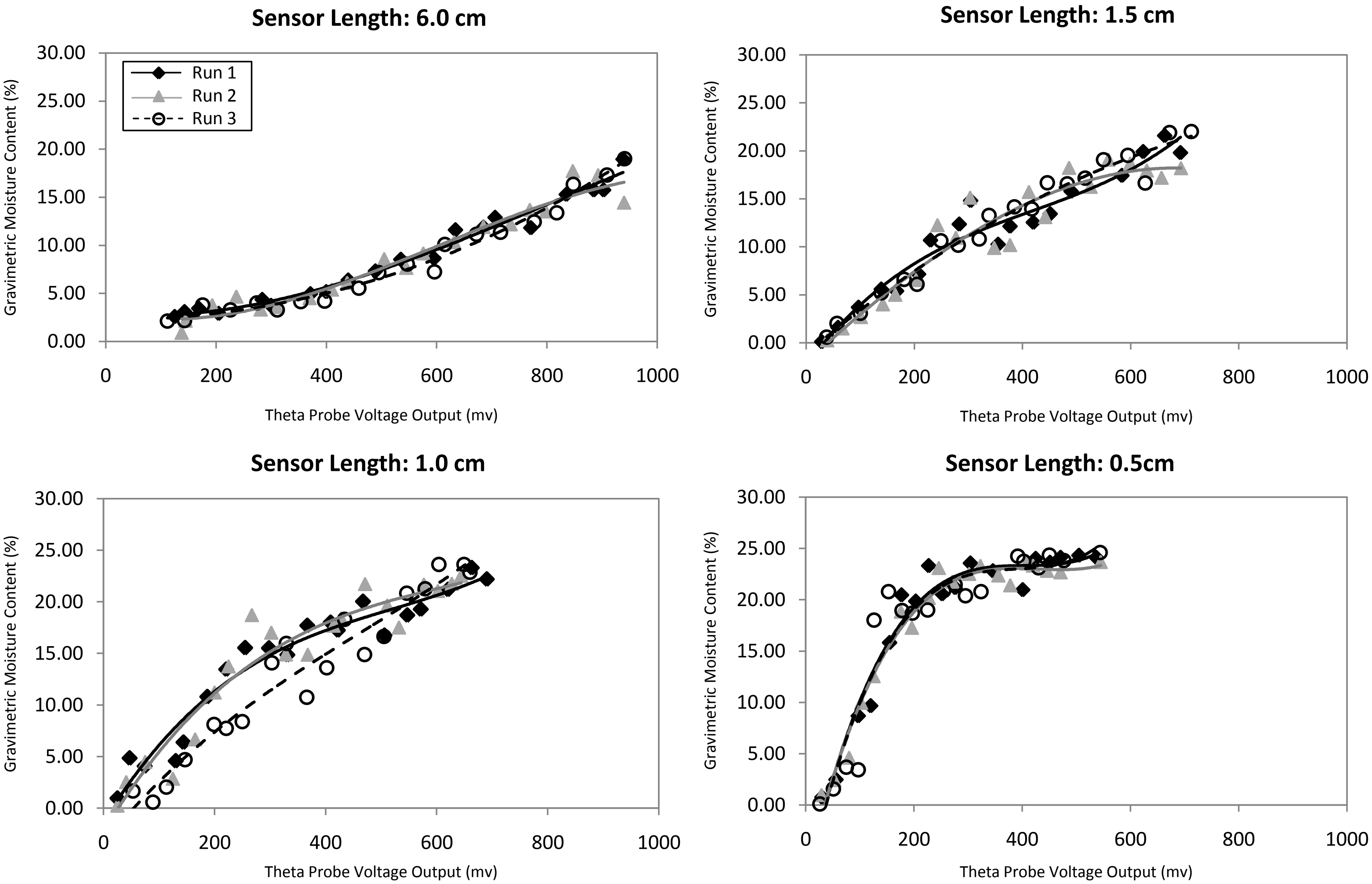


Figure 4.4: Third-order polynomial calibration relationships at sensor lengths 6.0, 1.5, 1.0 and 0.5 cm for Kill Devil Hills, North Carolina.

relationships for the 1.0 cm sensor length, and particularly at the 0.5 cm sensor length. For the 1.0 and 0.5 cm sensor lengths, the slope of the third-order relationship is much steeper than that of the linear relationship at both study site locations for moisture content values below roughly 20% (gravimetric). Above this value the slope of the third-order relationship becomes drastically flatter than that of the linear relationship. This suggests that the perceived sensitivity of the probe is considerably altered by the calibration function employed.

In addition to looking at the differences in the slope of the calibrations between the linear and third-order calibration relationships, the R^2 values and SE values were evaluated. R^2 values were used to evaluate the relative strength of the calibration relationships between gravimetric moisture content and voltage output. Table 4.1 is a summary of R^2 values for the linear and third-order relationships for the PINS and KDH sites. For the PINS, site the third-order relationship produced higher R^2 values for all three experimental runs at each of the four sensor lengths. Concurrently, the third-order relationship produced higher or equal R^2 values for all three experimental runs at each of the four sensor rod lengths than the linear relationship at the KDH site. This indicates that the third-order relationship generates a stronger calibration than the linear relationship.

SE values were used to evaluate the accuracy of the relationship in determining moisture content. For both study site locations, the linear relationship produces greatly increased SE values for each experimental run at each of the four sensor rod lengths than the third-order relationship (Table 4.2). These results indicate that a third-order relationship gives a more precise assessment of the Theta Probe’s ability to measure surface moisture contents than the linear relationship.

Table 4.1: R2 values for third-order polynomial and linear regression relationship at the Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, Texas

Calibration Equation	Sensor Length (cm)	Experimental Runs			Mean R^2
		1	2	3	
3rd order	6.0	0.96	0.96	0.89	0.94
	1.5	0.91	0.93	0.94	0.93
	1.0	0.96	0.92	0.97	0.95
	0.5	0.96	0.98	0.81	0.92
Linear	6.0	0.91	0.90	0.85	0.89
	1.5	0.88	0.90	0.88	0.89
	1.0	0.89	0.89	0.94	0.91
	0.5	0.91	0.93	0.70	0.85

Kill Devil Hills, NC

Calibration Equation	Sensor Length (cm)	Experimental Runs			Mean R^2
		1	2	3	
3rd order	6.0	0.98	0.95	0.98	0.97
	1.5	0.95	0.92	0.97	0.95
	1.0	0.95	0.92	0.94	0.94
	0.5	0.96	0.98	0.89	0.94
Linear	6.0	0.96	0.94	0.93	0.94
	1.5	0.83	0.87	0.96	0.89
	1.0	0.88	0.85	0.94	0.89
	0.5	0.69	0.73	0.68	0.70

Table 4.2: SE values (% gravimetric) for third-order polynomial and linear regression relationship at the Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, Texas

Calibration Equation	Sensor Length (cm)	Experimental Runs			Mean SE
		1-A	2-A	3-A	
3rd order	6.0	1.1	0.8	1.0	1.0
	1.5	2.0	1.8	1.7	1.8
	1.0	1.5	1.8	1.0	1.4
	0.5	1.6	1.3	3.0	2.0
Linear	6.0	1.7	1.0	1.1	1.3
	1.5	2.4	2.2	2.4	2.3
	1.0	2.5	2.1	1.5	2.1
	0.5	2.6	2.1	4.0	2.9

Kill Devil Hills, NC

Calibration Equation	Sensor Length (cm)	Experimental Runs			Mean SE
		1-A	2-A	3-A	
3rd order	6.0	0.7	1.1	0.8	0.9
	1.5	1.6	1.9	1.1	1.5
	1.0	1.5	2.0	1.8	1.7
	0.5	1.5	1.2	2.6	1.8
Linear	6.0	1.2	1.3	1.5	1.3
	1.5	2.5	2.4	1.4	2.1
	1.0	2.4	2.9	2.0	2.4
	0.5	4.4	4.1	4.9	4.5

4.2 Calibration Relationships

4.2.1 Influence of Sensor Length

A major question regarding the calibration of the Delta-T Theta Probe involves the variability and reliability of the calibration relationships as sensor rod length is decreased. Figures 4.5 and 4.6 illustrate the calibration relationships for various sensor rod lengths. Sensor length considerably influences the slope of the calibration curves. The slope of the curve reflects the sensitivity of the probes response to moisture levels. A mild slope indicates that the probe is

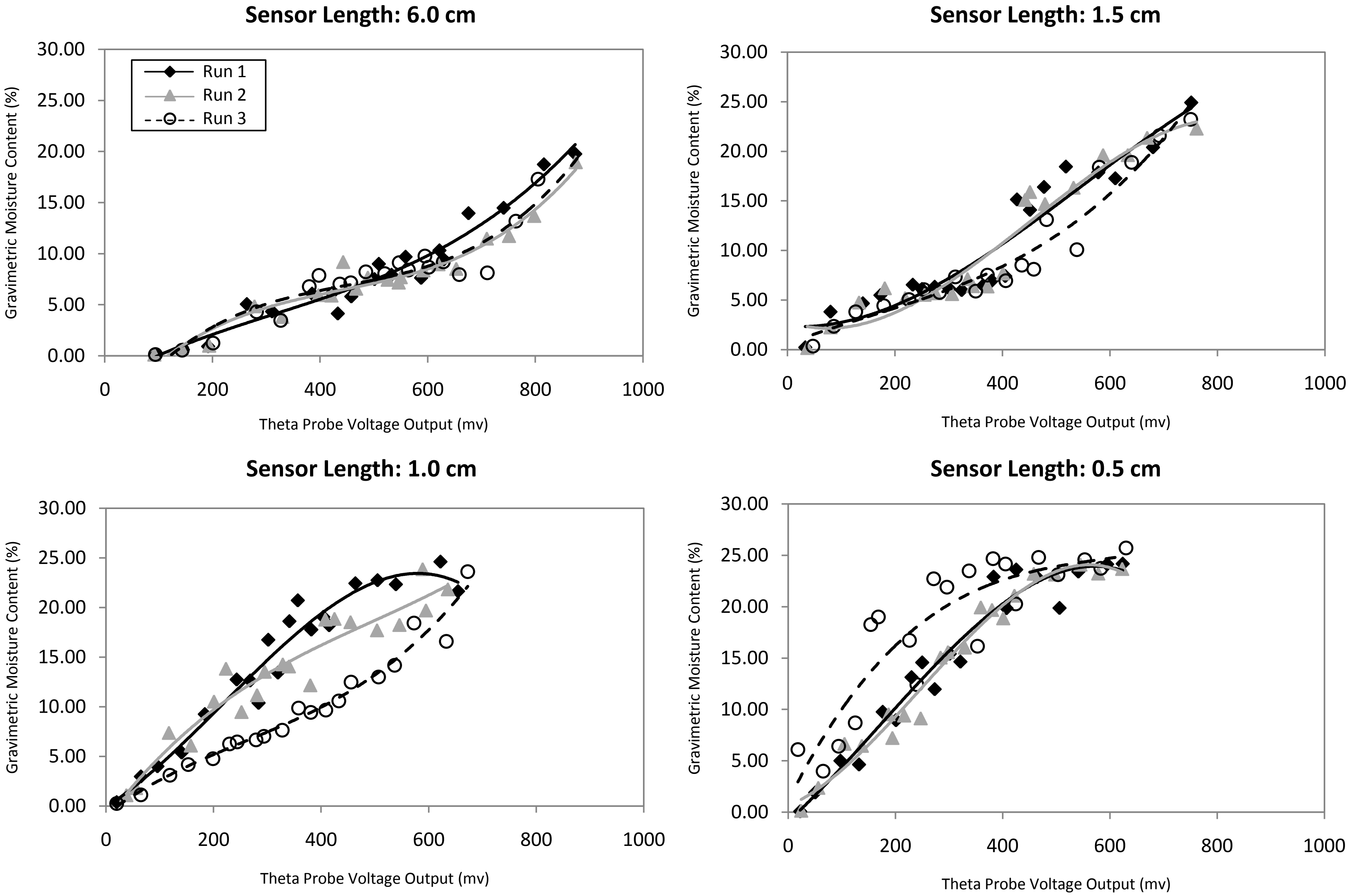


Figure 4.5: Calibration relationships at sensor lengths 6.0, 1.5, 1.0 and 0.5 cm for Padre Island National Seashore, Texas.

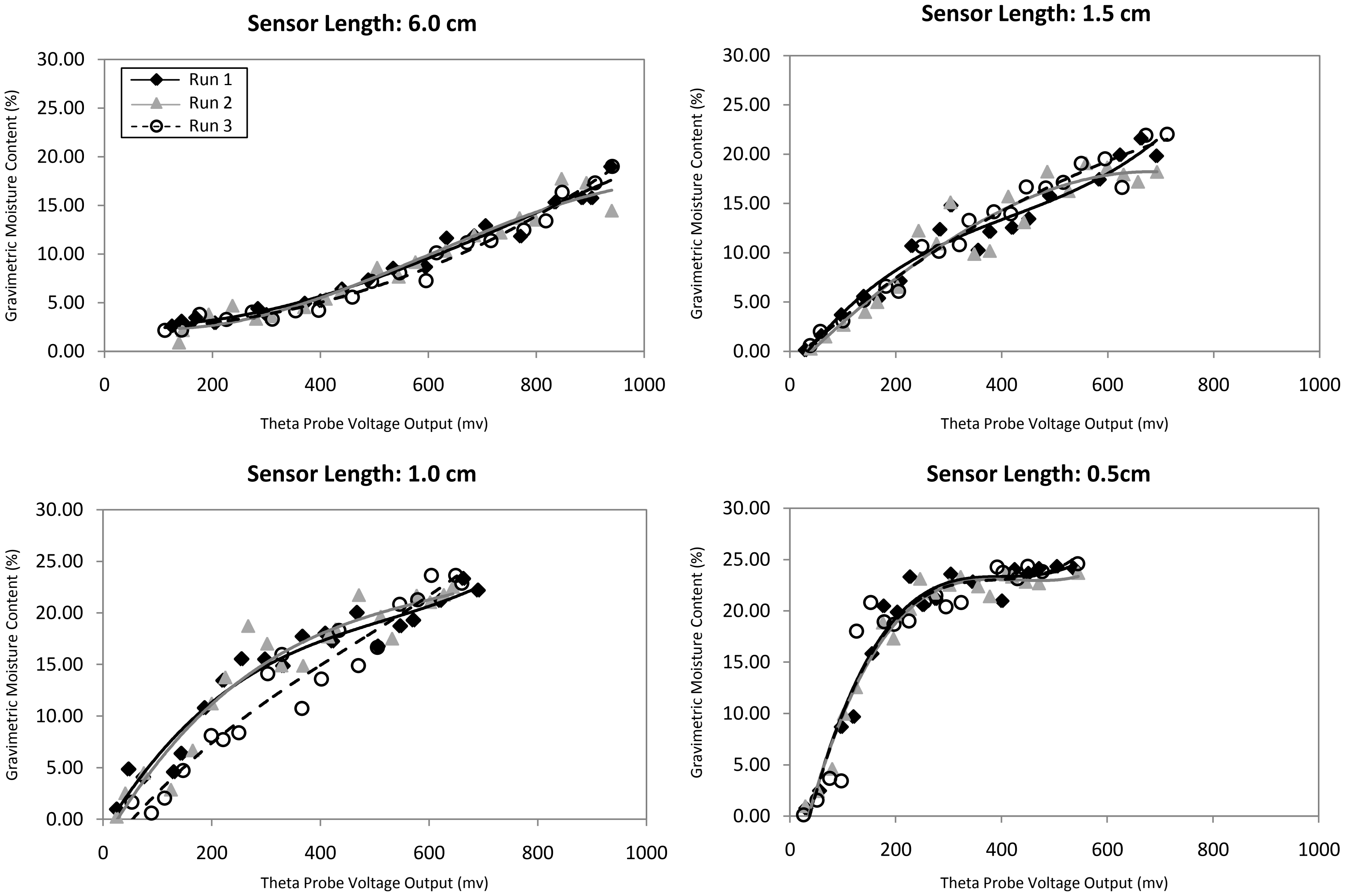


Figure 4.6: Calibration relationships at sensor lengths 6.0, 1.5, 1.0 and 0.5 cm for Kill Devil Hills, North Carolina.

very sensitivity to changes in moisture levels, while a steep slope indicates that the probe has a weak response to change in moisture levels. For both study sites, the slope of the calibrations increases with a decrease in the length of the sensor rod array. This indicates that the sensitivity of the Theta Probe weakens as the sensor length is shortened. There are, however; micro-variations in the slope of the calibrations for both study sites. For the PINS site, at the 6.0 and 1.5 cm sensor lengths the calibration slopes increase at moisture contents above 10 to 15% (gravimetric), whereas, at the 1.0 and 0.5 cm sensor lengths the calibration slopes begin to decrease above these moisture contents. For moisture content values below this value, the calibration slopes increase with decreasing sensor length at the 1.0 and 0.5 cm sensor length. Similar to the PINS site, at the KDH study site the slope of the calibrations at the 1.5, 1.0, and 0.5 cm sensor lengths become increasingly flatter at higher moisture content values compared to the 6.0 cm sensor length. At the 6.0 cm sensor length the slope of the calibrations begins to steepen at higher moisture contents. These results indicate that at higher moisture content values the sensitivity of the probe becomes more pronounced as the length of the sensor rod array shortens. At moisture content values below approximately 15% (gravimetric) the calibration slopes steepen with decreasing senor length for both study site locations. This indicates that the sensitivity of the probe weakens with a decrease in sensor length at low moisture content values.

These results designate that there is a shift in the sensitivity of the probes response to moisture content with a decrease in sensor length. The fact that the changes in sensitivity with decreasing sensor length occur for both study site locations indicates that they are systematic.

In addition to looking at how the sensor length influences the sensitivity of the Theta Probe, the influence that sensor length has on the strength of the relationship between gravimetric moisture content and voltage output was evaluate. The strength of the calibration relationship was analyzed using a third-order polynomial regression analysis. Table 4.3 gives the R^2 values for each of the experimental runs per sensor length at the PINS and KHD sites. Overall both study sites exhibit high R^2 values at each of the four sensor lengths. With the exception of experimental run three at the 0.5 cm lengths, which has an R^2 value of 0.81, all other experimental runs for both study site locations have R^2 values above 0.89 with a mean value of 0.94. This indicates a robust relationship between gravimetric moisture content and Theta Probe voltage output. Additionally, there is no observable reduction in R^2 values with a decrease in the sensor rod length. In fact, for four of the six experimental run one or more of the shortened-probe treatments showed a larger or equal R^2 value than the full 6.0 cm probe length. These results signify that the length of the sensor has no perceivable influence on the strength of the relationship between gravimetric moisture content and voltage output. This indicates that at shallow measurements lengths the Theta Probe is capable of producing very strong calibration relationships.

Table 4.3: R^2 values at all four sensor rod lengths for the Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, TX

Sensor Length (cm)	Experimental Runs 1	2	3	Mean R^2	Std. Deviation
6.0	0.96	0.96	0.89	0.94	0.04
1.5	0.91	0.93	0.94	0.93	0.02
1.0	0.96	0.92	0.97	0.95	0.03
0.5	0.96	0.98	0.81	0.92	0.09

Kill Devil Hills, NC

Sensor Length (cm)	Experimental Runs 1	2	3	Mean R^2	Std. Deviation
6.0	0.98	0.95	0.98	0.97	0.02
1.5	0.95	0.92	0.97	0.95	0.03
1.0	0.95	0.92	0.94	0.94	0.02
0.5	0.96	0.98	0.89	0.94	0.05

Standard error (SE) was measured to evaluate the accuracy of the Theta Probe in determining moisture content. There is a roughly 1% (gravimetric) moisture content increase in SE from the 6.0 cm sensor length to the 0.5 cm sensor length for both study sites (Table 4.4). SE values for the PINS site increase from a mean value of 1.0% (gravimetric) at the 6.0 cm length to mean values of 1.9%, 1.5% and 2.1% (gravimetric) at the 1.5, 1.0, and 0.5 cm lengths,

Table 4.4: SE values (% gravimetric) for the Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, TX					
Sensor Length (cm)	**Experimental Runs**			**Mean SE**	**Std. Deviation**
	1	**2**	**3**		
6.0	1.1	0.9	1.1	1.0	0.1
1.5	2.2	1.9	1.6	1.9	0.3
1.0	1.6	1.9	1.0	1.5	0.5
0.5	1.7	1.4	3.2	2.1	1.0

Kill Devil Hills, NC					
Sensor Length (cm)	**Experimental Runs**			**Mean SE**	**Std. Deviation**
	1	**2**	**3**		
6.0	0.7	1.1	0.8	0.9	0.2
1.5	1.6	1.9	1.1	1.5	0.4
1.0	1.5	2.1	1.9	1.8	0.3
0.5	1.6	1.2	2.6	1.8	0.7

respectively. For the KDH site, SE increases from a mean value of 0.8% (gravimetric) at the 6.0 cm length to mean values of 1.6%, 1.7%, and 1.8% (gravimetric) at the 1.5, 1.0 and 0.5 cm, respectively. These results signify a slight reduction in accuracy as sensor length is decreased, however; this reduction is not significantly different at the 95% confidence interval. Furthermore; the SE values fall below the associated accuracy range of approximately 3.5% (gravimetric) established by the manufacturer, as well as within accuracy ratings illustrated in the literature for a soil/field-specific calibration (Delta-T Devices, 1999; Tsegaye et al., 2004; Cosh et al., 2005; Yang and Davidson-Arnott, 2005). This suggests that the slight increase in error at the shorter sensor rod lengths is due to some combination of the small-scale variations in sediment compaction and composition, operator error within the field, and/or from uncertainties in determining ‘real’ moisture content within the lab from the field collected moisture samples rather than the response of the probe itself (Belly, 1987; Cosh, 2005; Delta-T Devices, 1999; Kaleita, 2005; Yang and Davidson-Arnott, 2005).

4.2.2 Influence of Grain Size

Grain size is one of the most important factors controlling beach hydrology. Since calibration relationships differ with moisture content and grain size, it is worthwhile to examine this issue in the context of beach sand. These findings will be applicable to a wider range of beaches and of use to other researchers.

Figure 4.7 is a comparison of the calibration relationships determined for fine (PINS) and medium (KDH) sediments. The calibration relationships between grain sizes are nearly identical at the 6.0 cm sensor length, particularly below moisture contents of 15% (gravimetric). Above this values, the slope of the calibrations begin to vary. This indicates that at moisture contents below approximately 15% (gravimetric) that grain size does not influence the sensitivity of the Theta Probe, however; at moisture contents above this value, grain size does influence the sensitivity of the probe, as the probe becomes less sensitive to changes in moisture at fine grain sizes compared to medium grain sizes. At the 1.5, 1.0 and 0.5 cm sensor lengths the calibrations are vastly different between grain sizes. Interestingly, fine sediment consistently predicts lower moisture content values than that of medium sediment, resulting in medium sediment producing considerably steeper slopes compared to fine sediment. This is particularly true for moisture content values less than 15% (gravimetric). This indicates that fine sediment exhibits a considerably stronger sensitivity to changes in moisture content than for medium sediment at lower moisture content values. At higher moisture content values, fine sediment and medium sediment generate similar moisture contents. This results in comparable calibration slopes between the two sediment sizes at the 1.5, 1.0 and 0.5 cm sensor lengths. This signifies that at high moisture contents that sediment grain size does not have any significant influence on the sensitivity of the probe. Overall, these results indicate that sediment grain size has a remarkable influence on the sensitivity of the Theta Probe. This is particularly true at the shorter probe lengths, where fine sediment has a more pronounced sensitivity than medium sediment at lower moisture content values.

Although there are differences between the calibration relationships for the different sediment sizes, the question remains regarding whether these differences produce disparity in the

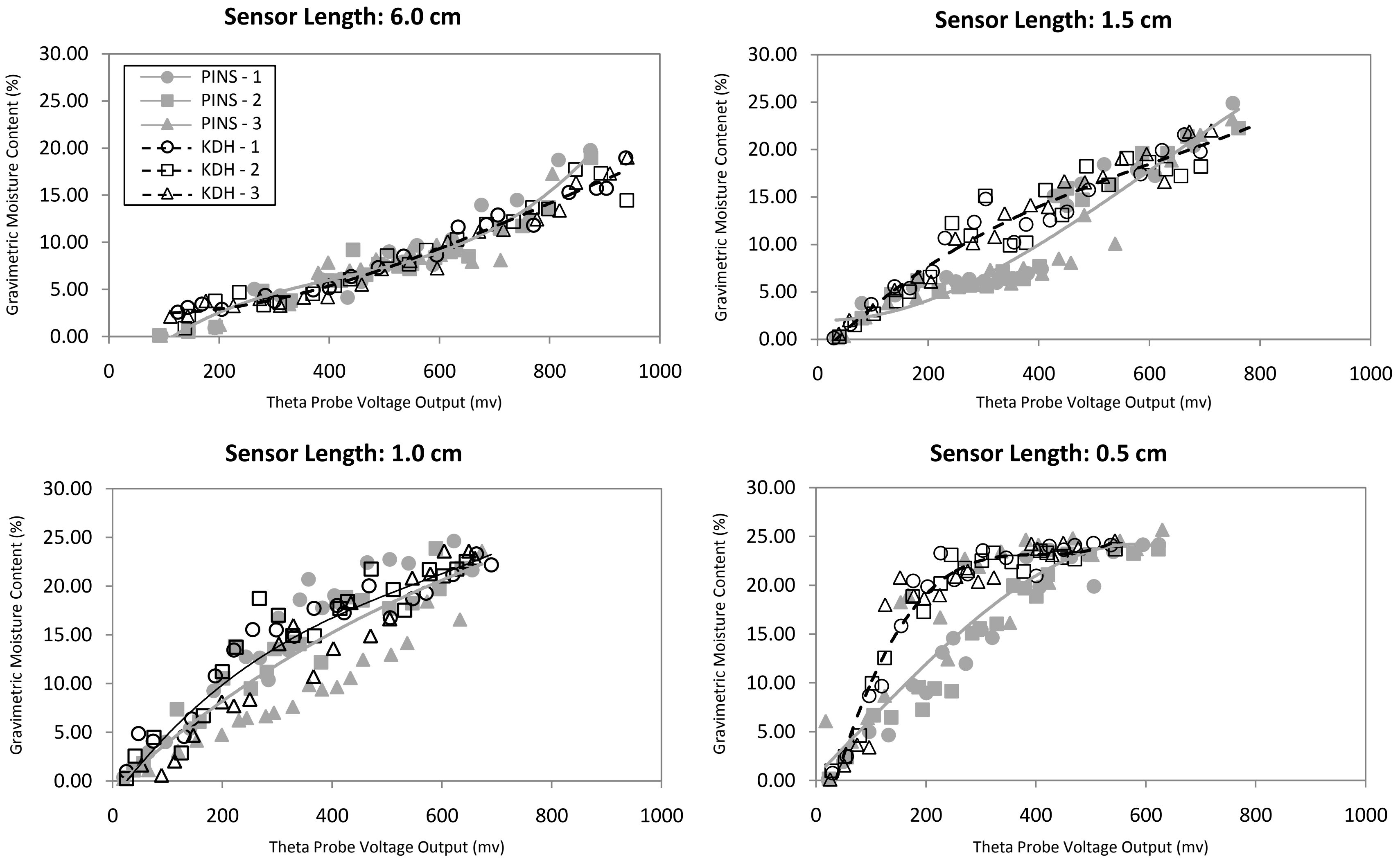


Figure 4.7: Calibration relationships of all three experimental runs for sensor lengths of 1.0 and 0.5 cm illustrating differences between grain sizes. The number corresponds to the experimental run, while the trend-line represents the mean calibration relationship from each of the three experimental runs.

reliability of the calibrations. An analysis of variance test on the R^2 and SE values was employed to investigate if grain size has any influence on calibration strength or accuracy of the Theta Probe. It was found that the R^2 values for each of the three experimental runs using probe A were not statistically different at a 95% confidence interval within the individual sensor rod lengths. In addition, the analysis of variance test determined that the SE values for each of the three experimental runs using probe A were not statistically different at a 95% confidence interval within the individual sensor rod lengths. These findings indicate that grain size has no significant influence on the Theta Probe's calibration strength or accuracy.

4.2.3 Repeatability

An important question regarding the utility of the Delta-T Theta Probe is the reliability of the probe to conduct repeatable moisture samples with a single probe. Figures 4.8 and 4.9 show comparisons of calibrations for the different experimental runs conducted for probe A at each sensor length for both study site locations. For the PINS study site, the 6.0 cm sensor lengths produce excellent repeatability between each of the experimental runs across the entire relationship. For the 1.5 and 0.5 cm sensor lengths, the repeatability of the Theta Probe is very good between experimental runs one and two, as the calibrations are nearly identical for each sensor length. At the 1.5 cm length, experimental run three produces moisture content values 3 to 4% (gravimetric) lower than runs one and two for moisture contents above approximately 8% (gravimetric). The variability between run three and runs one and two could be the result of outlier data points within the data set for experimental run three. Elimination of these data points drastically altered the calibration slope for this individual experimental run, vastly improving the repeatability between the calibrations (Figure 4.10). This suggests that the variance in the calibrations was influenced by outliers in the data set rather than the Theta Probe itself, and that

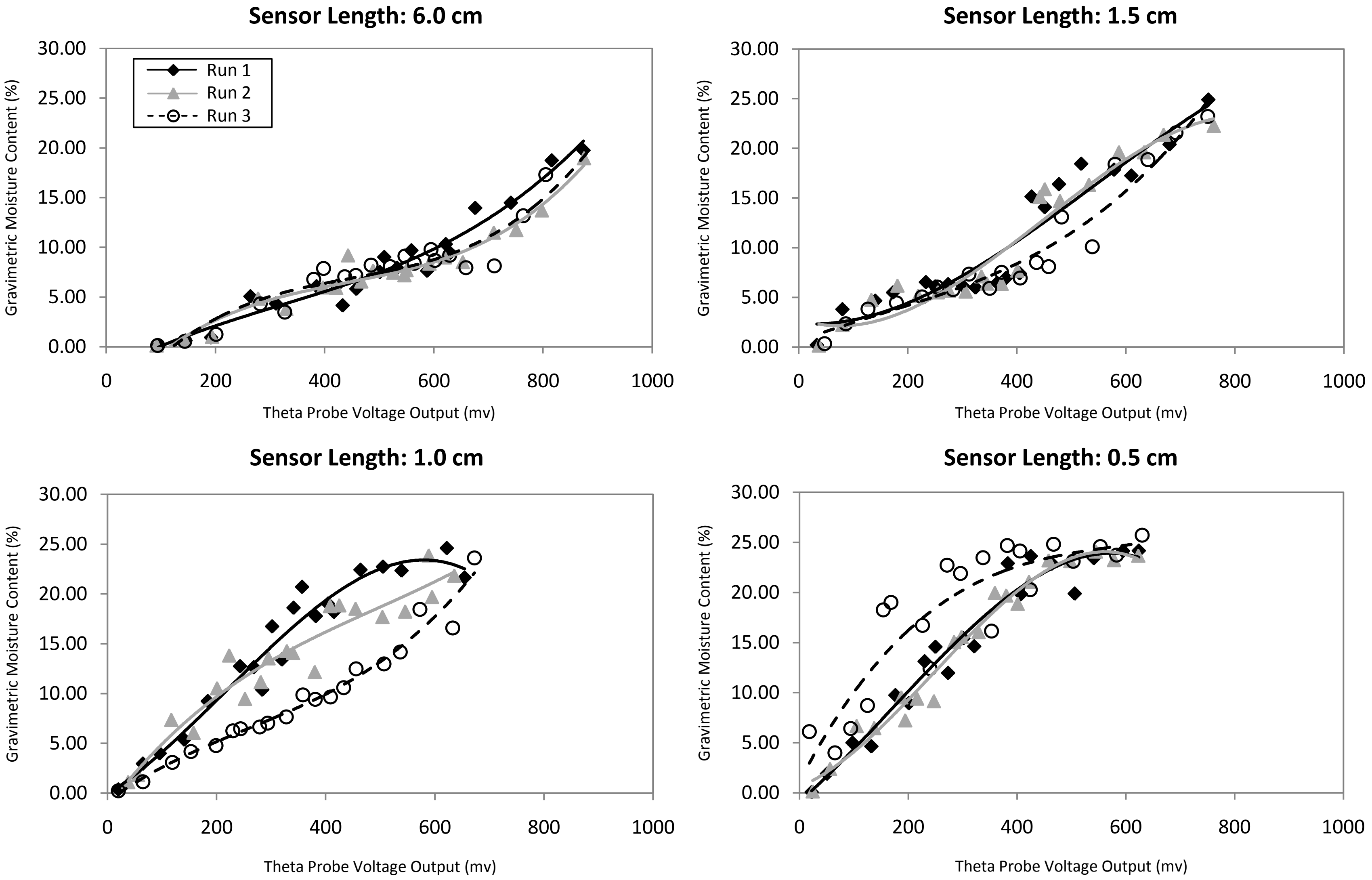


Figure 4.5: Calibration relationships at sensor lengths 6.0, 1.5, 1.0 and 0.5 cm for Padre Island National Seashore, Texas illustrating repeatability.

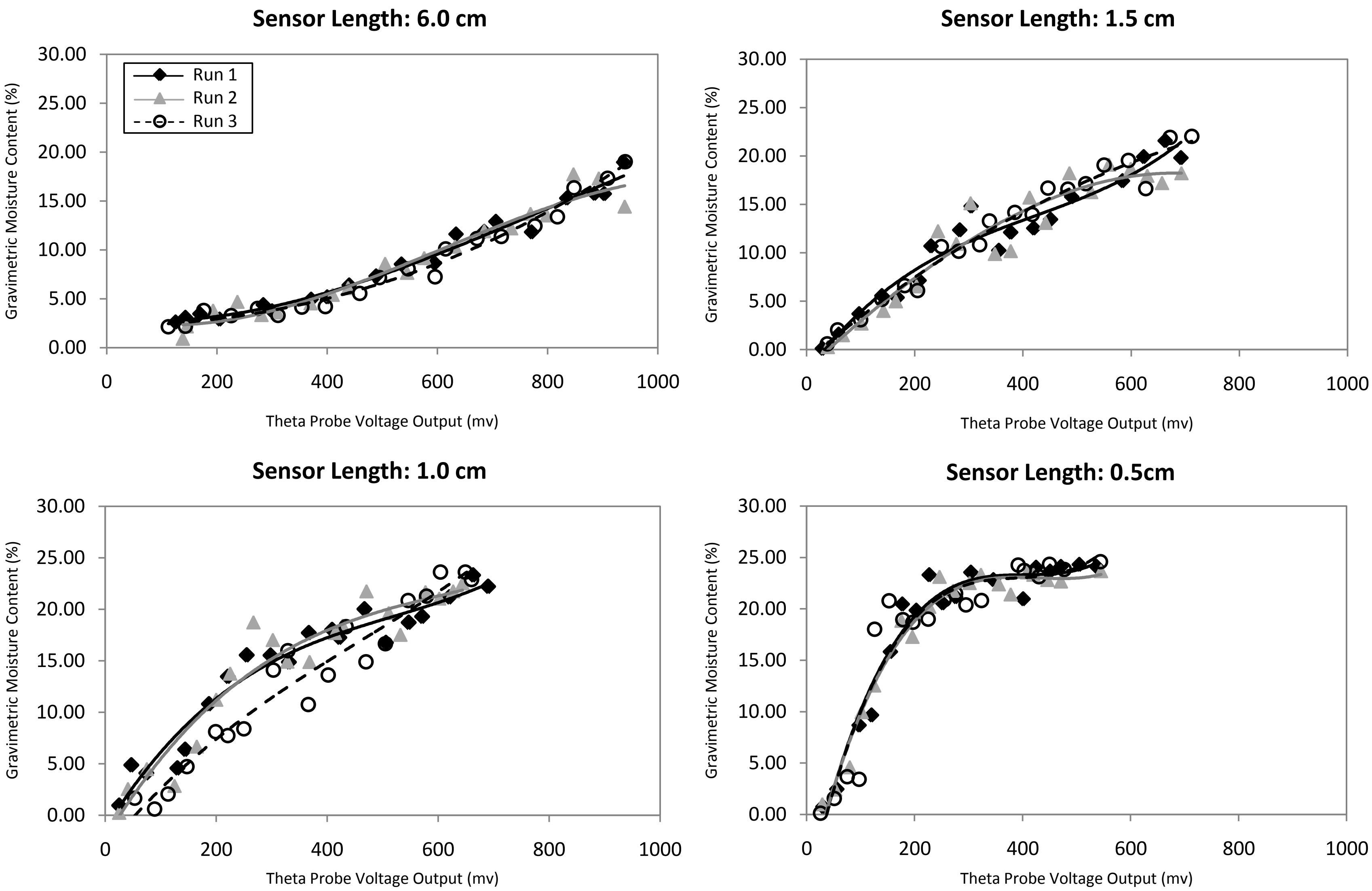
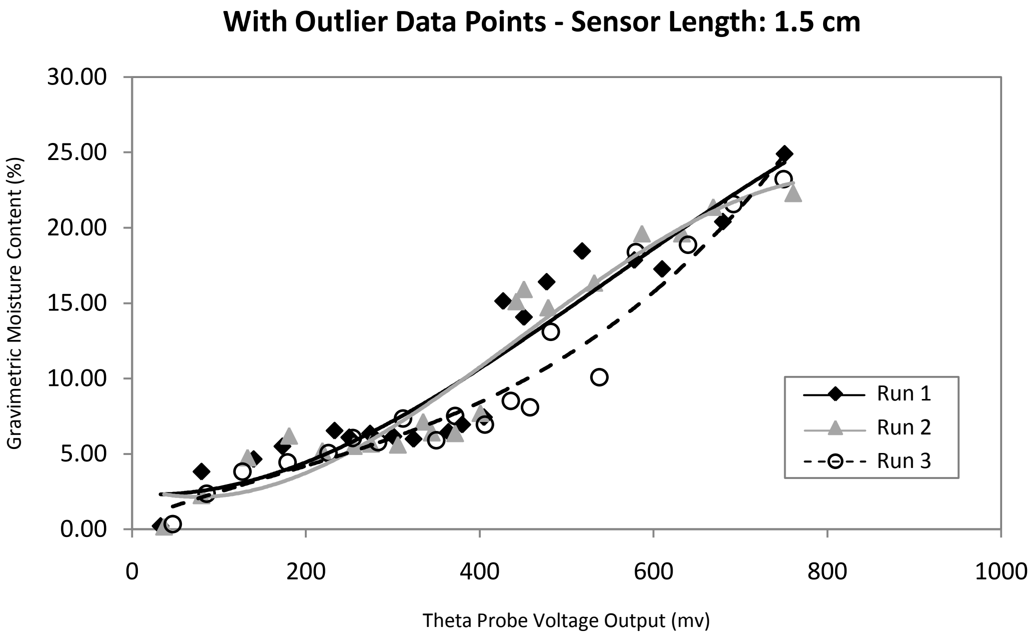


Figure 4.6: Calibration relationships at sensor lengths 6.0, 1.5, 1.0 and 0.5 cm for Kill Devil Hills, North Carolina illustrating repeatability.

the repeatability is considerably higher than initially believed. At the 0.5 cm sensor length, the calibration for experimental run three predicts moisture contents as much as 4 to 5% (gravimetric) higher than runs one and two. The poor degree of repeatability by experimental run three is perhaps due to operator error occurring either in the field or in the lab. The R^2 value of experimental run three is roughly 15% lower than runs one and two. Additionally, the SE value for experimental run three is approximately 1.5% (gravimetric) greater than the other two experimental runs (Table 4.7). This indicates that the variance between the calibrations at the 1.5 cm sensor length can be attributed to error by the operator either during measurement or collection of the moisture sample in the field, or in determining the moisture content during lab analysis than from the probe itself. The 1.0 cm sensor length has a considerable amount of variability between the calibrations for each of the three experimental runs. The calibrations for experimental runs one and two are very consistent up to a moisture content of roughly 10% (gravimetric). Above this value there is increased scatter in the data between the two runs. This results in differences in moisture contents exceeding 3% (gravimetric). The low degree of repeatability between these two calibrations is unexplainable because there are no major outliers in the data sets altering the calibrations. Additionally, the standard error values for both calibrations are very similar (Table 4.7). This suggests that the variance between the calibrations is not due to operator error. Furthermore, experimental run three produces distinctly lower moisture contents than runs one and two. A possible explanation for this high degree of variability could be that the experimental run was conducted on the morning after experimental runs one and two were conducted.

The repeatability of the Theta Probe for the KDH site is excellent at the 6.0, 1.5, and 0.5 cm sensor lengths. The 6.0 cm sensor rod length has an excellent level of repeatability


With Outlier Data Points - Sensor Length: 1.5 cm

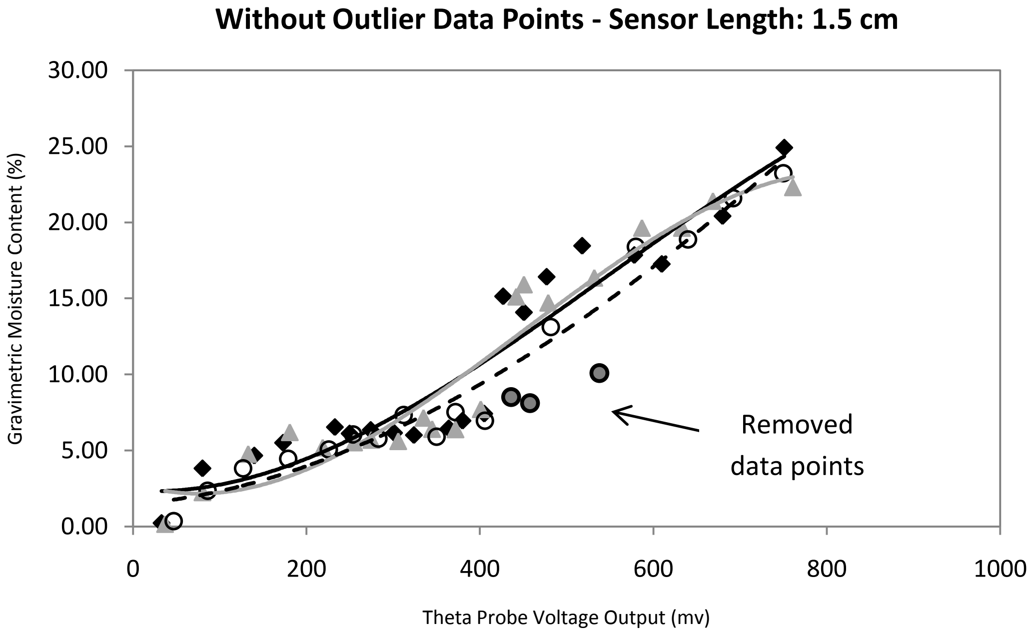

Without Outlier Data Points - Sensor Length: 1.5 cm

Figure 4.10: Illustration of improvement in repeatability at the 1.5 cm sensor length as outlier data point is removed from experimental run 3 data set for the PINS study site.

Table 4.7: SE values (% gravimetric) for experimental runs 1, 2, and 3 at the Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, TX

Sensor Rod Length (cm)	Experimental Runs			Mean SE	Std. Deviation
	1	2	3		
6.0	1.1	0.9	1.1	1.0	0.1
1.5	2.2	1.9	1.6	1.9	0.3
1.0	1.6	1.9	1.0	1.5	0.5
0.5	1.7	1.4	3.2	2.1	1.0

Kill Devil Hills, NC

Sensor Rod Length (cm)	Experimental Runs			Mean SE	Std. Deviation
	1	2	3		
6.0	0.7	1.1	0.8	0.9	0.2
1.5	1.6	1.9	1.1	1.5	0.4
1.0	1.5	2.1	1.9	1.8	0.3
0.5	1.6	1.2	2.6	1.8	0.7

throughout the entire calibration relationship. All three experimental runs are within 1% (gravimetric) moisture content of each other. At the 1.5 cm length, the repeatability of the probe is very good at moisture contents below 10% (gravimetric) for each of the three experimental runs. Above this value, there is increased scatter within the data, however; each of the three experimental runs are within 2% (gravimetric) moisture content of each other. For the 1.0 cm sensor rod length there is a very strong level of repeatability between experimental runs one and two across the entire calibration relationship. However, experimental run three predicts notably lower moisture content value than runs one and two. As with the 0.5 cm sensor length at the PINS study site, the variance between the calibrations for experimental runs one and two and experimental run three could be attributed to experimental run three being conducted on the morning after experimental runs one and two were conducted.

Overall, both study sites indicate the repeatability of the Theta Probe can be very high. Interesting when an experimental run was conducted on the morning after the other two experimental runs were conducted, the experimental run produced markedly lower moisture contents. Possible explanations for this finding could be due to differing environmental conditions, such as soil temperature (Kaleita et al., 2005a), sediment compaction by wave or aeolian transport, humidity, or salinity.

4.2.4 Interchangeability

Aside from the repeatability, it is important to understand the utility of the Theta Probe to conduct reliable moisture samples between two different probes. Figures 4.11 and 4.12 depict variability in the calibration relationships between experimental run one conducted for probe A and probe B for the PINS and KDH study sites. For the PINS study site, the interchangeability of the Theta Probe appears very poor, particularly at the 6.0, 1.5 and 1.0 cm sensor lengths. For the 6.0 cm length differences in moisture content are as much as 3% (gravimetric) between the calibrations. The calibration for probe B predicts markedly higher moisture content values below roughly 8% (gravimetric) and above this moisture content value the calibration predicts markedly lower moisture content values. At the 1.5 and 0.5 cm sensor lengths, the interchangeability between the calibrations is very poor at moisture content values greater than roughly 8% (gravimetric) for the 1.5 cm sensor length, and approximately 10% (gravimetric) for the 0.5 cm sensor length. A possible explanation for the variance in the calibrations at the 6.0 and 1.5 cm sensor lengths could be due to a few outliers in the data sets. At the 6.0 cm sensor length removing these data points did not improve the variance between the calibrations for probe A and probe B (Figure 4.13). This indicates that the interchangeable variance is not caused by a few outliers in the data set. At the 1.5 cm sensor length, however; removing the outlier data points within the data set from probes A and B resulted in a vast improvement in the interchangeable variance between the calibrations (Figure 4.14). The variance at the 0.5 cm sensor length could be a result of operator error occurring either in the field or the lab, as there are no major outliers in the data set for probe A. The difference in standard error between the calibration for probes A and B is nearly 1% (gravimetric) with a probe A having a value of 1.8% and probe B a value of 1.0% (Table 4.8). This indicates that the poor degree of

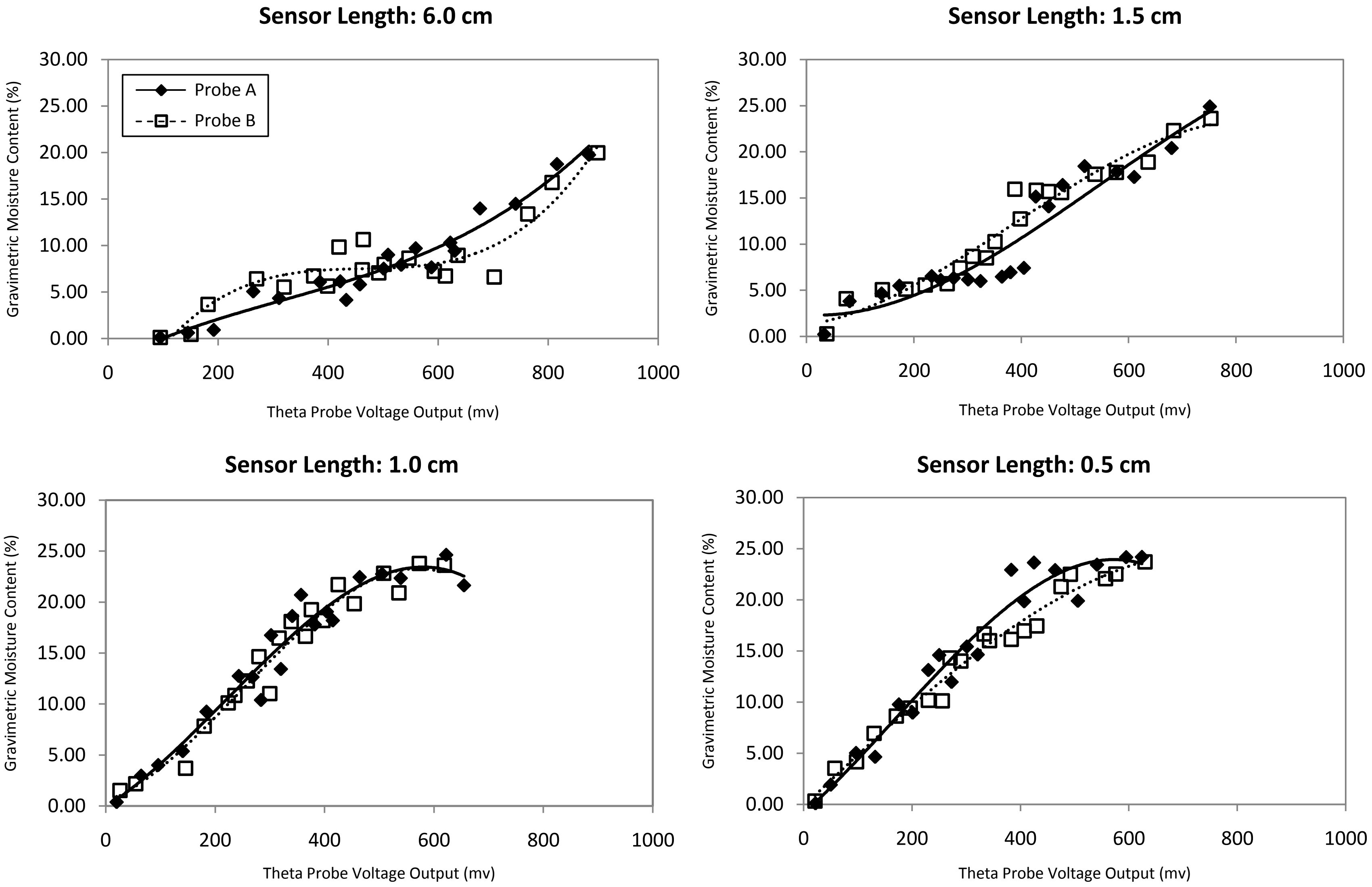


Figure 4.11: Calibration relationships for moisture content below 10 % (gravimetric) at sensor lengths of 6.0, 1.5, 1.0 and 0.5 cm for experimental run 1 using probe A and probe B for Padre Island National Seashore, Texas illustrating interchangeability.

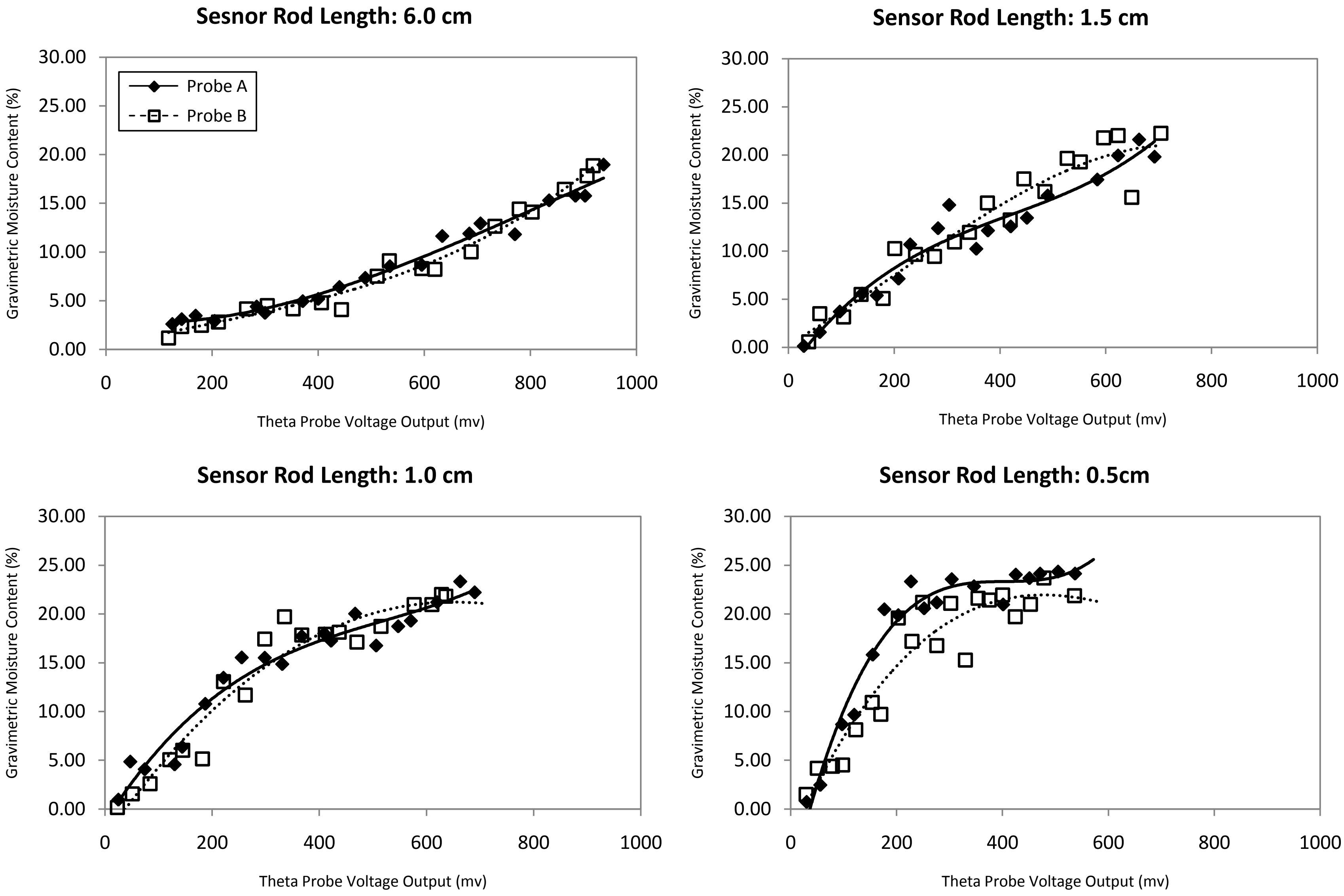
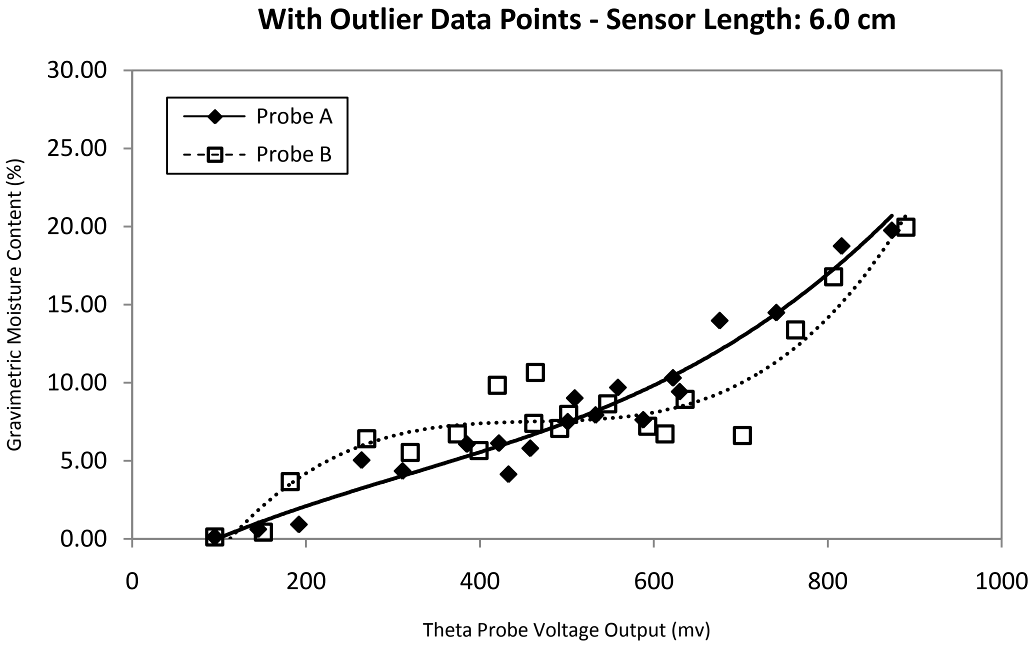


Figure 4.12: Calibration relationships for moisture content below 10 % (gravimetric) at sensor lengths of 6.0, 1.5, 1.0 and 0.5 cm for experimental run 1 using probe A and probe B for Kill Devil Hill, North Carolina illustrating interchangeability.



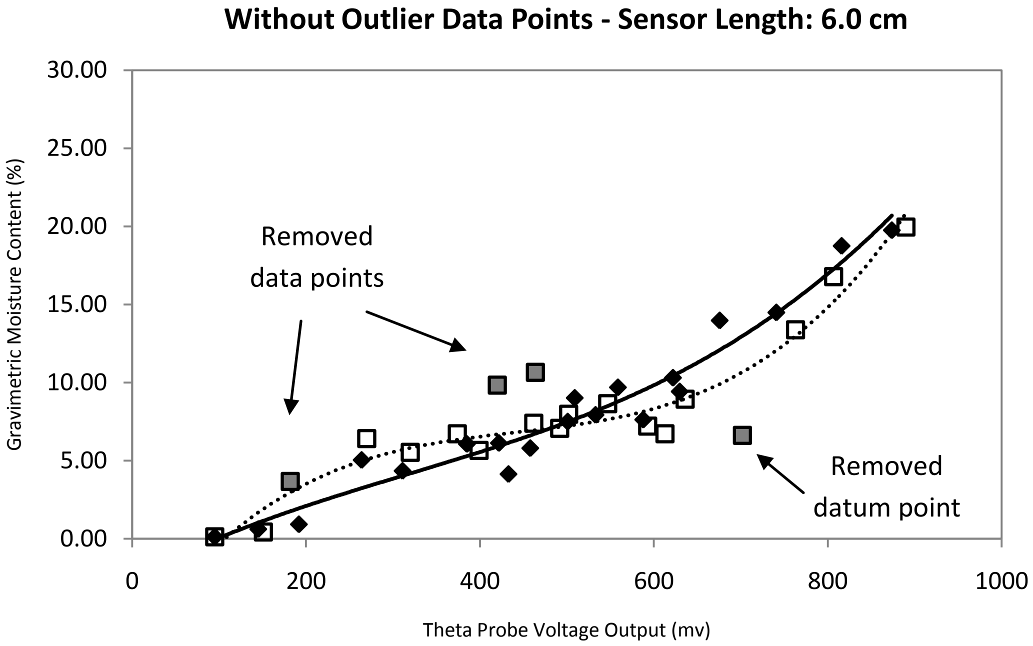
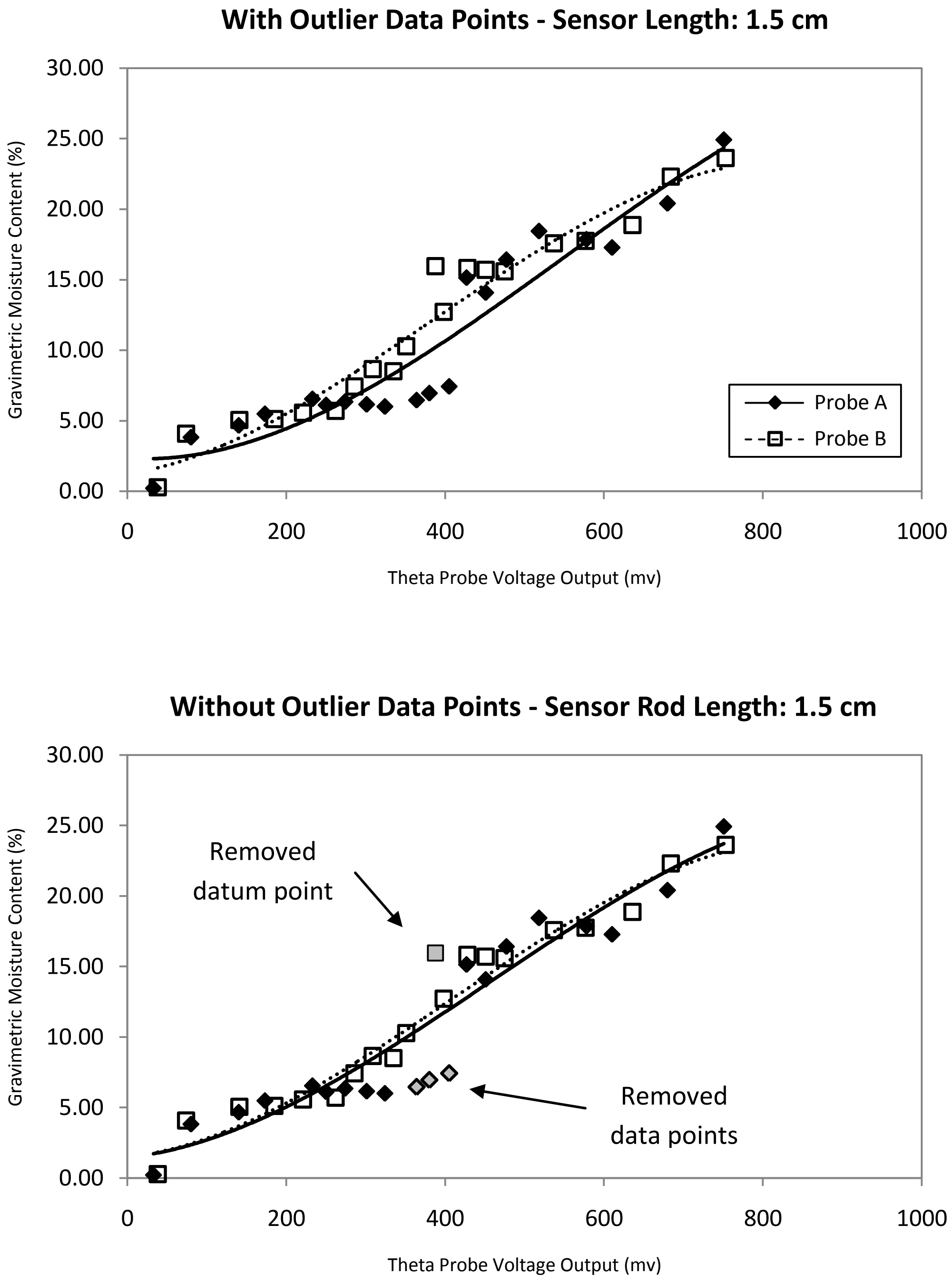


Figure 4.13: Illustration of minimal improvement in interchangeability at the 6.0 cm sensor length as outlier data points are removed from the probe B data set for the PINS study site.


With Outlier Data Points - Sensor Length: 1.5 cm

Without Outlier Data Points - Sensor Rod Length: 1.5 cm

Figure 5.14: Illustration of improvement in interchangeability at the 1.5 cm sensor length as outlier data points are removed from probes A and B data sets for the PINS study site.

Table 4.8: SE values (% gravimetric) for Probe A and Probe B at the Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, TX				
Sensor Length (cm)	**Probe**		**Mean SE**	**Std. Deviation**
	A	**B**		
6.0	1.1	1.2	1.2	0.1
1.5	2.2	1.5	1.9	0.5
1.0	1.6	1.4	1.5	0.1
0.5	1.7	1.0	1.4	0.5

Kill Devil Hills, NC				
Sensor Length (cm)	**Probe**		**Mean SE**	**Std. Deviation**
	A	**B**		
6.0	0.8	0.8	0.8	0.0
1.5	1.6	1.8	1.7	0.1
1.0	1.5	1.9	1.7	0.3
0.5	1.6	2.4	2.0	0.6

interchangeability is a product of operator error within the field or lab as there is increased scatter throughout the entire data set instead a few bad data points. At the 1.0 cm sensor rod length the calibration relationships are nearly identical. There is a difference in moisture content on average of less than 0.5% (gravimetric) between the calibrations from probe A and B. This indicates that there is excellent interchangeability between the two probes at the 1.0 cm sensor length. For KDH site, the interchangeability between probe A and probe B is very strong, at the 6.0 and 1.0 cm sensor lengths. The calibration relationships for both sensor lengths have a difference in moisture content on average of less than 1% (gravimetric) between the calibrations from probe A and B. At the 1.5 cm sensor length, the calibration relationships exhibit a strong level of interchangeability up to about 10% (gravimetric). At moisture contents above this value there is a notable increase in the variance between the calibrations, resulting in differences in moisture contents exceeding 3% (gravimetric). The variability at the 1.5 cm sensor length is unexplainable, since removal of the outlier within the data sets for probe A and B did not considerably improve the variability between the two probes (Figure 4.15). The 0.5 cm length has very poor interchangeability between the two probes throughout the entire calibration relationship. On average the calibration for probe B produces gravimetric moisture content values that are 3% lower than probe A. As seen in section 4.3.3, the variance between the calibrations here can perhaps be attributed to experimental run for probe B being conducted

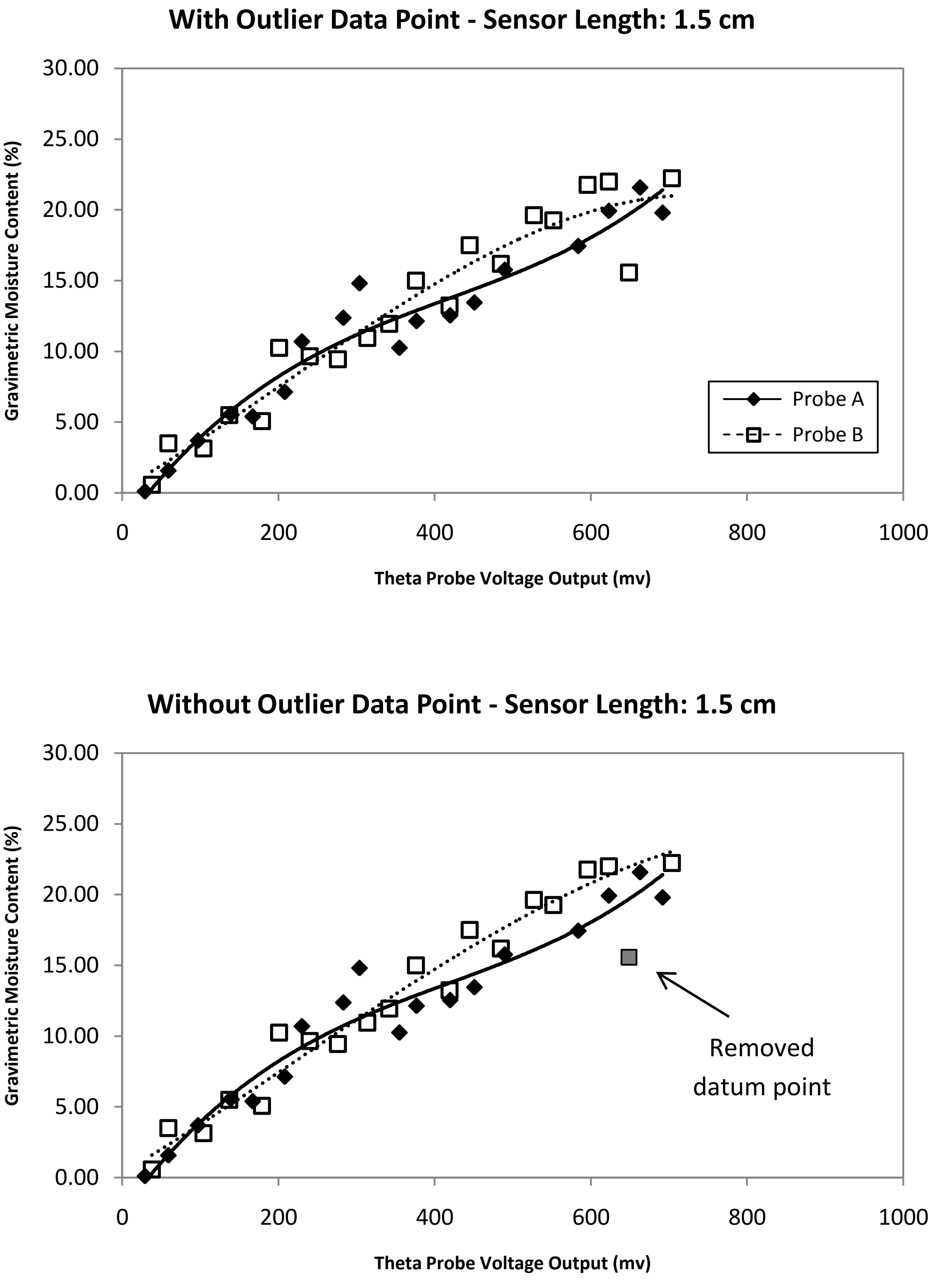


Figure 5.15: Illustration of improvement in interchangeability at the 1.5 cm sensor length as outlier data point is removed from the probe B data set for the KDH study site.

on the following morning as the experimental run for probe A was conducted.

Overall, there are mixed results regarding the level of interchangeability for the Theta Probe for both study site locations. Nevertheless, a large portion of the variance can be explained by either outliers in the data sets or by operator error in the field or lab. Again, when an experimental run was conducted on the morning after the subsequent experimental run was conducted, that experimental run produced noticeably lower moisture content values.

4.3 Summary

Examination of the calibration relationship between gravimetric moisture content and Theta Probe voltage output revealed several important findings concerning the utility of the Delta-T Theta Probe. First, a third-order polynomial calibration relationship provides improved accuracy over a linear calibration relationship for both study site locations. At each sensor length the third-order polynomial provided higher R2 values and lower SE values than the linear calibration for both study sites. This indicates that the calibration function employed dramatically influences the strength and accuracy of the Theta Probe. Second, the length of the sensor rod array significantly affects the sensitivity of the Theta Probe. For lower moisture content values, less than approximately 15% (gravimetric), the sensitivity of the probe weakens as the sensor length decreases. For higher moisture content values, greater than 15% (gravimetric), the sensitivity of the probe increases as sensor rod length decreases. In addition, there is no observable reduction in R^2 values with a decrease in the sensor rod length. In fact, for every experimental run one or more of the experimental runs with a shortened-probe showed a larger or equal R^2 value than the full 6.0 cm probe length. These results signify that the length of the sensor has no perceivable influence on the strength of the relationship and that the Theta Probe is capable of producing very strong calibration relationships at shallow measurement lengths. Furthermore, SE values depicted a slight reduction in accuracy of the Theta Probe as sensor length is decreased, however; this reduction is not significantly different at the 95% confidence interval. In addition, the SE values for each of the experimental runs at both study sites fell below the associated accuracy range of approximately 3.5% (gravimetric) established by the manufacturer as well as within accuracy ratings illustrated in the literature. Third, sediment grain size has a remarkable influence on the sensitivity of the Theta Probe. This is particularly true at the shorter probe lengths, where fine sediment has a more pronounced sensitivity than medium sediment at lower moisture content values. An analysis of variance test determined there to be no statistical difference between grain sizes for both R^2 and SE values at the 95% confidence interval. This indicates that grain size has no significant influence on the calibration strength or accuracy. Finally, there are mixed results regarding the level of repeatability and interchangeability of the Theta Probe for both study site locations. For both the PINS and KDH study sites there were multiple sensor lengths with very poor repeatability and interchangeability between the calibrations. Nevertheless, a large portion of the variance can be explained by either outliers in the data sets or by operator error in the field or lab. Interestingly, when an experimental run was conducted on the morning after the other experimental run/s were conducted for that sensor length, that experimental run produced markedly lower moisture contents. Possible explanations for this could due to differing environmental conditions, such as soil temperature (Kaleita et al., 2005a), sediment compaction by wave or aeolian transport, humidity, or salinity. Each of these are possible explanations as more research is needed to identify the influence that each may have on the calibrations.

Chapter 5

Evaluation of Calibration Relationship for Gravimetric Moisture Contents Less than 10%

Understanding the calibration relationships for gravimetric moisture contents below 10% is especially important because little aeolian sediment transport is thought to occur above this value. This chapter will examine calibration relationships for gravimetric moisture content for values less than 10%. Calibration relationships will be developed using a standard linear regression analysis, following Atherton et al. (2001) and Yang and Davidson-Arnott (2005). First, the influence of sensor rod length will be discussed. Second, the influence of sediment size on the calibration relationships will be investigated. The final two sections in this chapter will assess the repeatability and interchangeability of the Delta-T Theta Probes.

5.1 Calibration Relationships

5.1.1 Influence of Sensor Length

Figures 5.1 and 5.2 illustrate the calibration relationships between Theta Probe voltage response and gravimetric moisture content (< 10%) for various sensor rod lengths for the PINS and KDH sites. Sensor rod length clearly has a pronounced effect on the slope of the calibration relationships, which describe the sensitivity of the probe's response to moisture levels. A flatter slope identifies that the Theta Probe is more sensitive to changes in moisture content, while a steeper slope reflects a lower degree of sensitivity. For the PINS and KDH study sites there is an increase in the mean slope of the calibration relationships as sensor rod length decreases (Table 5.1). For the PINS site the mean slope increases by a factor of 2.6 and 2.7 as sensor rod length decreases from a length of 6.0 cm to lengths of 1.0 and 0.5 cm, respectively. Interestingly, there is no change in slope of the calibration relationship between the 6.0 and 1.5 cm sensor rod lengths or between the 1.0 and 0.5 cm sensor rod lengths. The slopes of the calibration

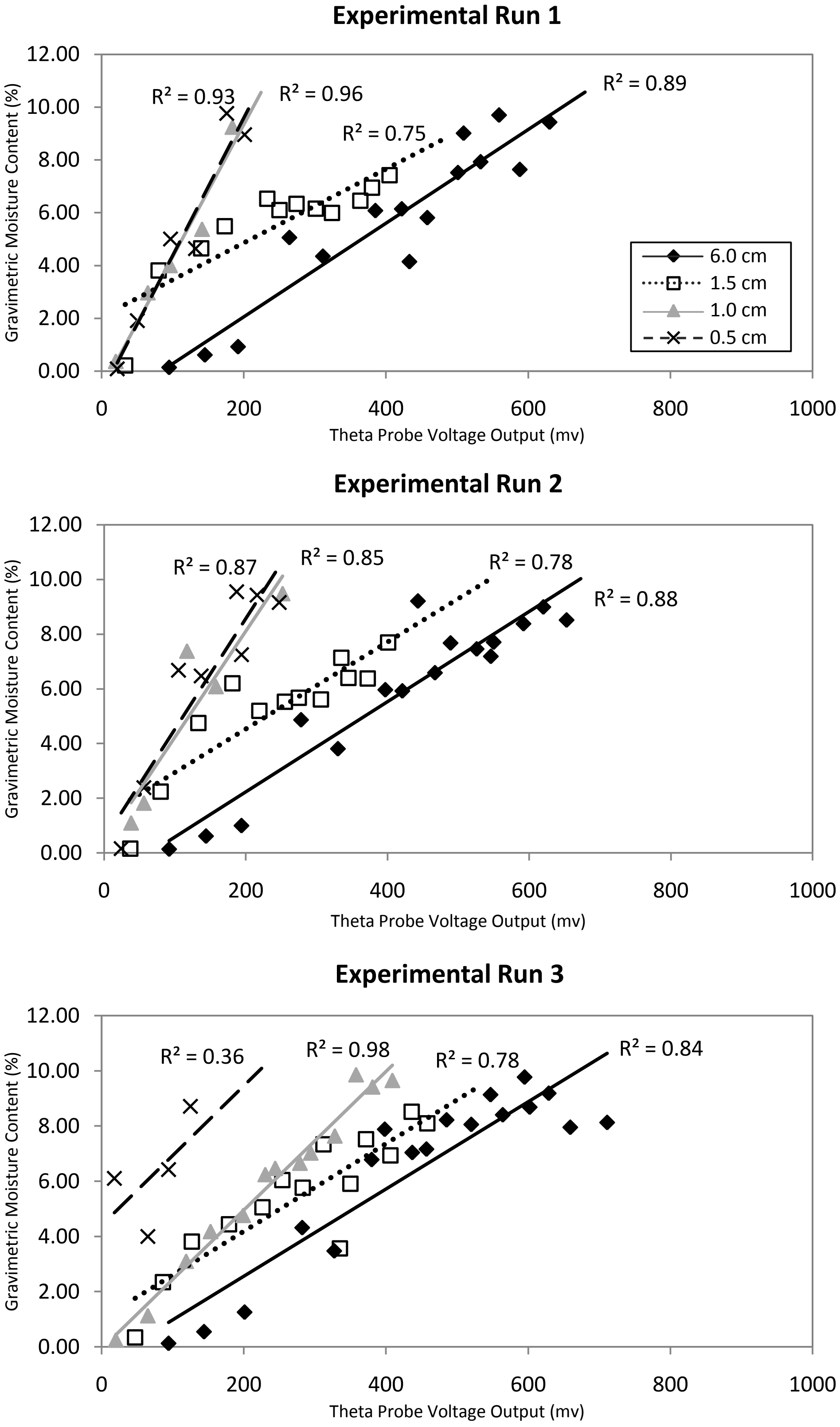


Figure 5.1: Linear calibration relationships at sensor rod lengths 6.0, 1.5, 1.0 and 0.5 cm using probe A for Padre Island National Seashore, Texas.

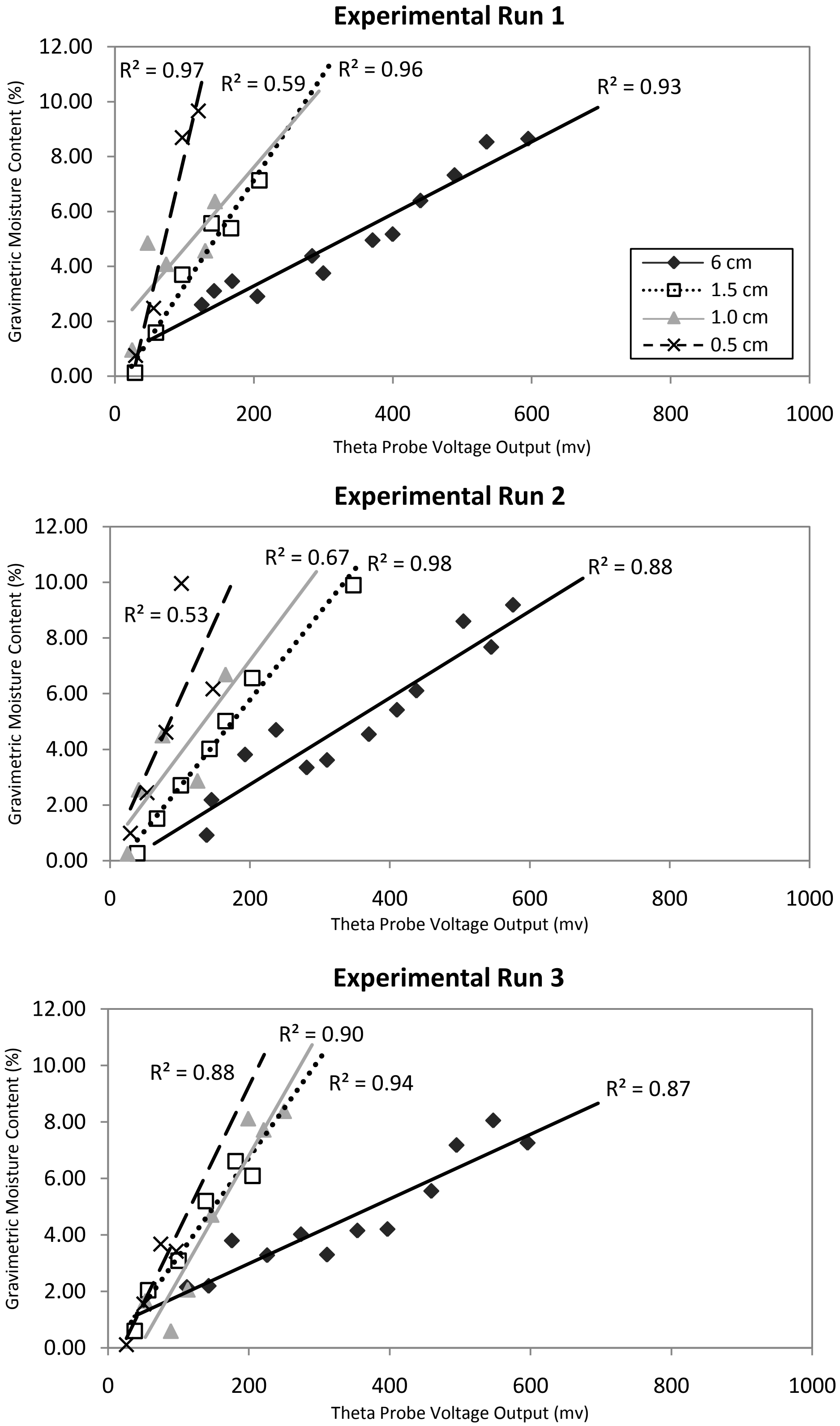


Figure 5.2: Linear calibration relationships at sensor rod lengths 6.0, 1.5, 1.0 and 0.5 cm using probe A for Kill Devil Hills, North Carolina.

Table 5.1: Calibration slopes for Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, TX					
Sensor Length (cm)	**Experimental Run**			**Mean Slope**	**Std. Deviation**
	1	**2**	**3**		
6.0	0.017	0.012	0.015	0.015	0.003
1.5	0.014	0.015	0.015	0.015	0.001
1.0	0.050	0.038	0.025	0.038	0.013
0.5	0.052	0.040	0.025	0.039	0.014

Kill Devil Hills, NC					
Sensor Length (cm)	**Experimental Run**			**Mean Slope**	**Std. Deviation**
	1	**2**	**3**		
6.0	0.013	0.015	0.011	0.013	0.002
1.5	0.038	0.031	0.034	0.034	0.004
1.0	0.029	0.033	0.043	0.035	0.007
0.5	0.110	0.055	0.051	0.072	0.033

relationships for the KDH study site increased by a factor of 2.6, 2.7 and 5.5 from the 6.0 cm sensor rod length to lengths of 1.5, 1.0 and 0.5 cm. These results demonstrate that sensor rod length greatly affects the sensitivity of the probe and that the sensitivity of the probe becomes less pronounced as the length of the sensor rod array shortens. Additionally, the standard deviation appears to increase as probe length decreases. This indicates that the reliability of the relationship decreases with probe length.

Overall, the R^2 values for both study sites indicate strong calibration relationships (Table 5.2). This indicates that sensor length does not have any demonstrable effect on the strength of the calibration relationship. There is no consistent reduction in R^2 values as sensor length is decreased. In fact, for every experimental run one or more of the shortened-probe treatments showed a larger R^2 value than the full 6.0 cm probe length. Relationship strength does become more variable at the two shortest sensor lengths. The increased variability in R^2 values at the two shortest sensor lengths could be influenced by the number of moisture samples used for analysis. Figure 5.3 depicts there to be increased scatter in R^2 values for both study sites when the data set is composed of 5 or less moisture samples. All four R^2 values that are below 0.70 were composed of data sets with 5 or less moisture samples. This suggests that the number of moisture samples used during analysis can influence the strength of the relationship. When a data set is composed of a small number of samples, outliers within the data set magnify the error.

Table 5.2: R^2 values for the Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, TX					
Sensor Length (cm)	**Experimental Run** **1**	 **2**	 **3**	**Mean R^2**	**Std. Deviation**
6.0	0.89	0.88	0.84	0.87	0.03
1.5	0.75	0.78	0.78	0.77	0.02
1.0	0.96	0.85	0.98	0.93	0.07
0.5	0.93	0.87	0.36	0.72	0.31

Kill Devil Hills, NC					
Sensor Length (cm)	**Experimental Run** **1**	 **2**	 **3**	**Mean R^2**	**Std. Deviation**
6.0	0.93	0.88	0.87	0.89	0.03
1.5	0.96	0.98	0.94	0.96	0.02
1.0	0.59	0.67	0.90	0.72	0.16
0.5	0.97	0.53	0.88	0.79	0.23

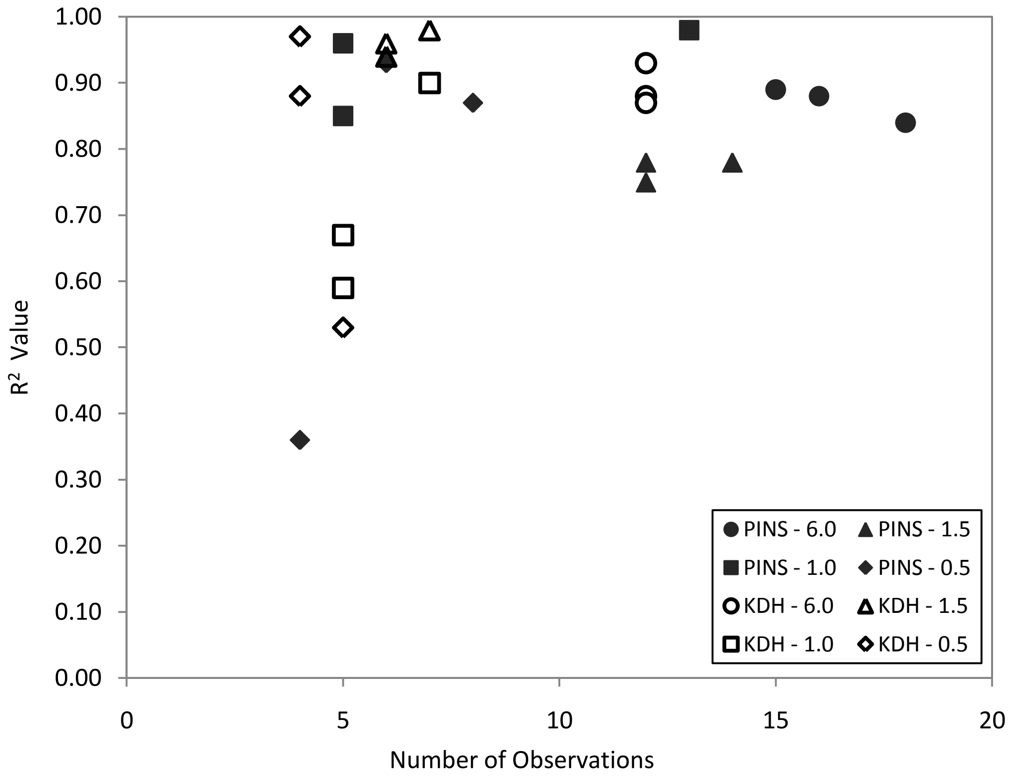


Figure 5.3: R^2 values plotted against the number of observations per data set.

In addition to R^2 values, standard error (SE) was calculated to assess the accuracy of the Theta Probe. Table 5.3 gives the SE values for the PINS and KDH sites. As with R^2 values, there is no consistent reduction in SE values at either study site as sensor rod length is decreased. This suggests that observed error of the calibration relationship is not a consequence of the shortening of the sensor rod array. The manufacturers reported accuracy for the Theta Probe

Table 5.3: SE values (% gravimetric) for Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, TX					
Sensor Length (cm)	**Experimental Run**			**Mean SE**	**Std. Deviation**
	1	**2**	**3**		
6.0	1.2	1.1	1.4	1.2	0.2
1.5	1.0	1.1	1.2	1.1	0.1
1.0	0.7	1.6	0.5	0.9	0.6
0.5	1.1	1.4	1.9	1.5	0.4

Kill Devil Hills, NC					
Sensor Length (cm)	**Experimental Run**			**Mean SE**	**Std. Deviation**
	1	**2**	**3**		
6.0	0.6	0.9	0.8	0.8	0.2
1.5	0.7	0.5	0.6	0.6	0.1
1.0	1.5	1.6	1.2	1.4	0.2
0.5	1.0	2.8	0.7	1.5	1.1

itself is ± 0.7% (gravimetric). SE values, for the most part, are quite close to the manufacturer's accuracy rating for both study sites. This suggests that error in the calibrations is a consequence of error built into the Theta Probe and not a product of the shortening of the sensor rod array. These results indicate the Theta Probe is very reliable as the sensor length is decreased.

Sensor length clearly influences the slope of the calibration relationships, which describes the sensitivity of the probe's response to moisture levels. As the sensor rod array is shortened the sensitivity of the probe becomes less pronounced for both study site locations. Sensor rod length does not, however; have any influence on the strength of the calibration relationship. There is no consistent reduction in R^2 values as sensor length is decreased. Relationship strength does become more variable, however; at the two shortest sensor lengths. As with R^2 values, there is no consistent reduction in SE values as sensor rod length is decreased at either study site. SE values for both study sites are quite close to the manufacturer's accuracy rating, suggesting that error in the calibrations is a consequence of error built into the Theta Probe itself and not a result of the shortening of the sensor rod array.

5.1.2 Influence of Grain Size

Figure 5.5 compares the calibration relationships determined for fine (PINS) and medium (KDH) sediments. Based on the results of an analysis of variance test the calibration slopes are not significantly different at the 95% confidence interval between grain sizes at sensor lengths of

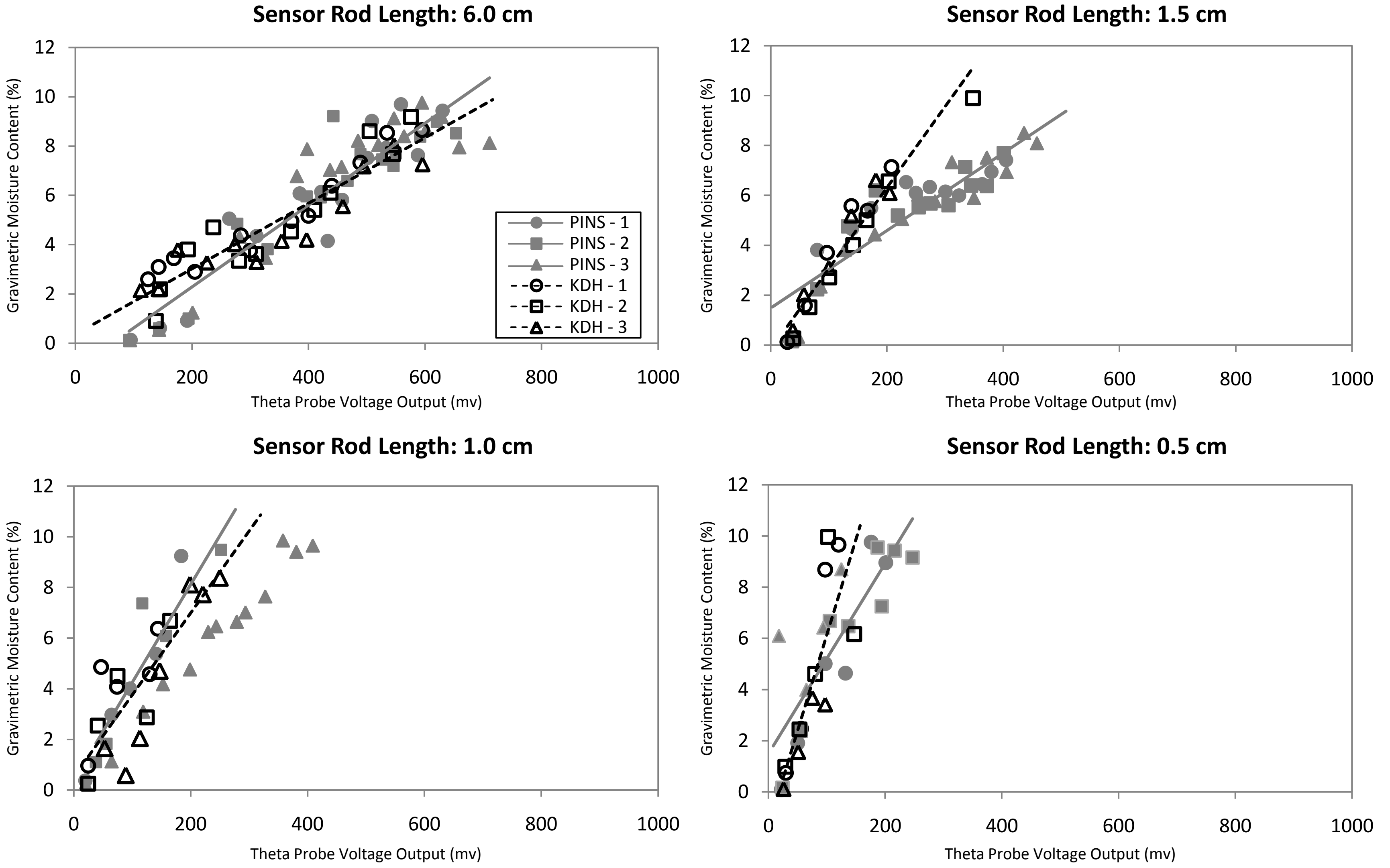


Figure 5.5: Linear calibration relationships of all three experimental runs for sensor lengths of 1.0 and 0.5 cm illustrating differences between Padre Island National Seashore, Texas (PINS) and Kill Devil Hills, North Carolina (KDH). The number corresponds to the experimental run, while the trend-line represents the mean slope from each of the three experimental runs.

6.0, 1.0 and 0.5 cm. This indicates that the sensitivity of the Theta Probe is not influenced by sediment size. However, the calibration slopes with the 1.5 cm sensor length differ significantly at the 95% confidence interval (Table 5.4). The mean slope of the calibration relationships for the medium grain size is over two times that of the mean slope for the fine grain size with a value of 0.034 for medium grain size compared to 0.015 for fine grain size. There is no obvious explanation for the variance in the calibration slopes at the 1.5 cm sensor length. The standard deviation for both grain sizes is very low, indicating that the mean slope is not subjective to any outliers in the data set. Aside from the findings at the 1.5 cm sensor length, these results indicate that sediment size does not influence the sensitivity of the Theta Probe.

With a few exceptions, the calibrations typically for medium sediment had somewhat higher R^2 values than the fine sediments. However, an analysis of variance test showed that the R^2 values for sensor rod lengths of 6.0, 1.0, and 0.5 cm are not significantly different at the 95% confidence interval. The 1.5 cm sensor length again proved to be the exception with R^2 values that differed significantly between grain sizes (Table 5.5). As with the calibration slopes there is no obvious explanation for the variance in R^2 values at the 1.5 cm sensor length. The standard deviation for both grain sizes is very low, again indicating that the mean R^2 value is not subjective to outliers in the data sets. Aside from the findings at the 1.5 cm sensor length, these results suggest that grain size does not influence the strength of the calibration relationships.

In general, medium sediment is associated with a higher level of accuracy than fine sediment (Table 5.6). The SE values for the experimental runs at sensor lengths of 6.0, 1.5, and 0.5 cm are consistently lower by an average of almost 0.5% (gravimetric) for medium sediment compared to fine sediment. At the 1.0 cm sensor length, however; the fine sediment produce an average of roughly 0.5% (gravimetric) increase in SE values over medium grain. These results

Table 5.4: Calibration slopes for Padre Island National Seashore and Kill Devil Hills study sites illustrating statistical difference between grain sizes at the 1.5 cm sensor length.

Padre Island National Seashore, TX					
Sensor Length (cm)	**Experimental Run**			**Mean Slope**	**Std. Deviation**
	1	**2**	**3**		
6.0	0.017	0.012	0.015	0.015	0.003
1.5	0.014	0.015	0.015	0.015**	0.001
1.0	0.050	0.038	0.025	0.038	0.013
0.5	0.052	0.040	0.025	0.039	0.014

Kill Devil Hills, NC					
Sensor Length (cm)	**Experimental Run**			**Mean Slope**	**Std. Deviation**
	1	**2**	**3**		
6.0	0.013	0.015	0.011	0.013	0.002
1.5	0.038	0.031	0.034	0.034**	0.004
1.0	0.029	0.033	0.043	0.035	0.007
0.5	0.110	0.055	0.051	0.072	0.033

** Statistically different at the 95% confidence interval ($p\text{-value} \leq 0.05$)

Table 5.5: R^2 values for the Padre Island National Seashore and Kill Devil Hills study sites illustrating statistical difference between grain sizes.

Padre Island National Seashore, TX					
Sensor Length (cm)	**Experimental Run**			**Mean R^2**	**Std. Deviation**
	1	**2**	**3**		
6.0	0.89	0.88	0.84	0.87	0.03
1.5	0.75	0.78	0.78	0.77**	0.02
1.0	0.96	0.85	0.98	0.93	0.07
0.5	0.93	0.87	0.36	0.72	0.31

Kill Devil Hills, NC					
Sensor Length (cm)	**Experimental Run**			**Mean R^2**	**Std. Deviation**
	1	**2**	**3**		
6.0	0.93	0.88	0.87	0.89	0.03
1.5	0.96	0.98	0.94	0.96**	0.02
1.0	0.59	0.67	0.90	0.72	0.16
0.5	0.97	0.53	0.88	0.79	0.23

** Statistically different at the 95% confidence interval ($p\text{-value} \leq 0.05$)

Table 5.6: SE values (% gravimetric) for Padre Island National Seashore and Kill Devil Hills study sites.

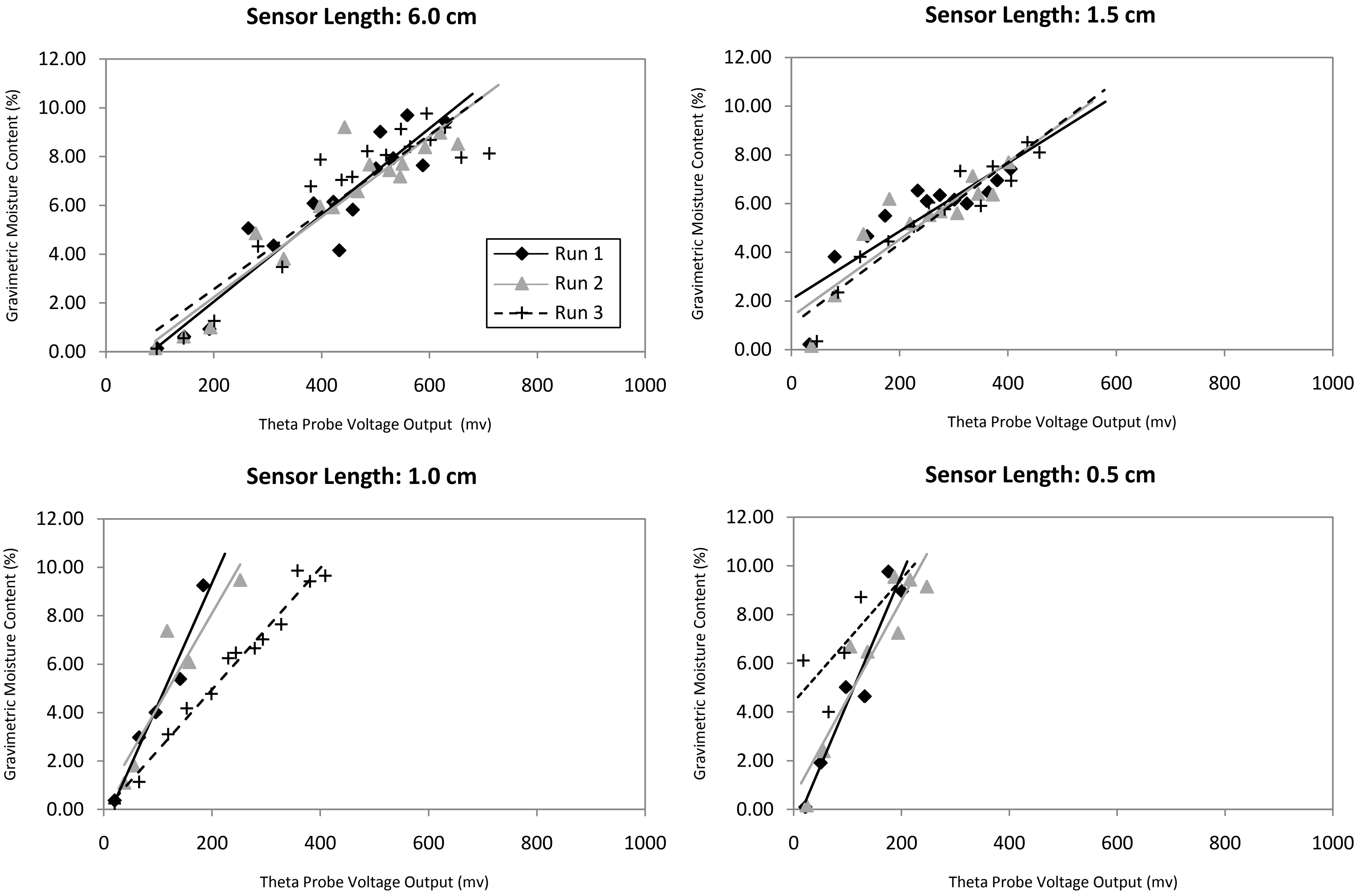
Padre Island National Seashore, TX					
Sensor Length (cm)	**Experimental Run**			**Mean SE**	**Std. Deviation**
	1	**2**	**3**		
6.0	1.2	1.1	1.4	1.2	0.2
1.5	1.0	1.1	1.2	1.1	0.1
1.0	0.7	1.6	0.5	0.9	0.6
0.5	1.1	1.4	1.9	1.5	0.4

Kill Devil Hills, NC					
Sensor Length (cm)	**Experimental Run**			**Mean SE**	**Std. Deviation**
	1	**2**	**3**		
6.0	0.6	0.9	0.8	0.8	0.2
1.5	0.7	0.5	0.6	0.6	0.1
1.0	1.5	1.6	1.2	1.4	0.2
0.5	1.0	2.8	0.7	1.5	1.1

suggest that grain size does influence the accuracy of the Theta Probe. The reason for this is uncertain, but could be attributed to the difference in the soil compaction, composition, structure, and texture between the two sediments.

5.1.3 Repeatability

Figures 5.6 and 5.7 show comparisons of calibrations for the different experimental runs conducted for probe A at each sensor length for both study site locations. For the PINS study site, the 6.0 and 1.5 cm sensor lengths produce excellent repeatability between each of the experimental runs. The calibration relationships for each of the experimental runs have on average a less than 0.5% (gravimetric) variance in moisture content throughout the entire moisture content range, for both sensor lengths. Furthermore, the standard deviations of the calibration slopes are low. There are, however; considerable differences between the calibration relationships for the 1.0 and 0.5 cm sensor lengths. Experimental run three for the 1.0 cm sensor length vastly underestimates moisture content compared to runs one and two. This results in a distinctively flatter calibration slope with a value of 0.025 compared to values 0.050 and 0.038 for runs one and two, respectively. This increase in variance between the calibration relationships is also evidenced by an increase in the standard deviation of the calibration slopes. As illustrated in chapter 5, a possible explanation for this variance could due to differing environmental conditions as experimental run three was conducted on the morning after experimental runs one and two were conducted. At the 0.5 cm sensor length the calibration relationship for experimental run three overestimates moisture content values below 8% (gravimetric) by an average of approximately 3% (gravimetric) compared to runs one and two. The variability between run three and runs one and two is perhaps due to an outlier data point within the data set for experimental run three. Eliminating this data point drastically alters the calibration slope for this individual experimental run, however; the standard deviation for the calibration slopes increases from a value of 0.014 to a value of 0.019. This indicates that the repeatable variance is not influenced by the outlier data point within the data set suggesting that the poor repeatability is not a cause of operator error. The repeatability of the Theta Probe for the KDH site is very good at the 6.0 and 1.5 cm sensor lengths. For the 6.0 cm sensor length, the variance in moisture content between each of the calibration relationships is on average 0.7% (gravimetric). The calibrations, however; do increase in variance above these values.



Sensor Length: 6.0 cm

Sensor Length: 1.5 cm

Sensor Length: 1.0 cm

Sensor Length: 0.5 cm

Figure 6.7: Calibration relationships for moisture content below 10 % (gravimetric) at sensor lengths of 6.0, 1.5, 1.0 and 0.5 cm for Padre Island National Seashore, Texas illustrating repeatability.

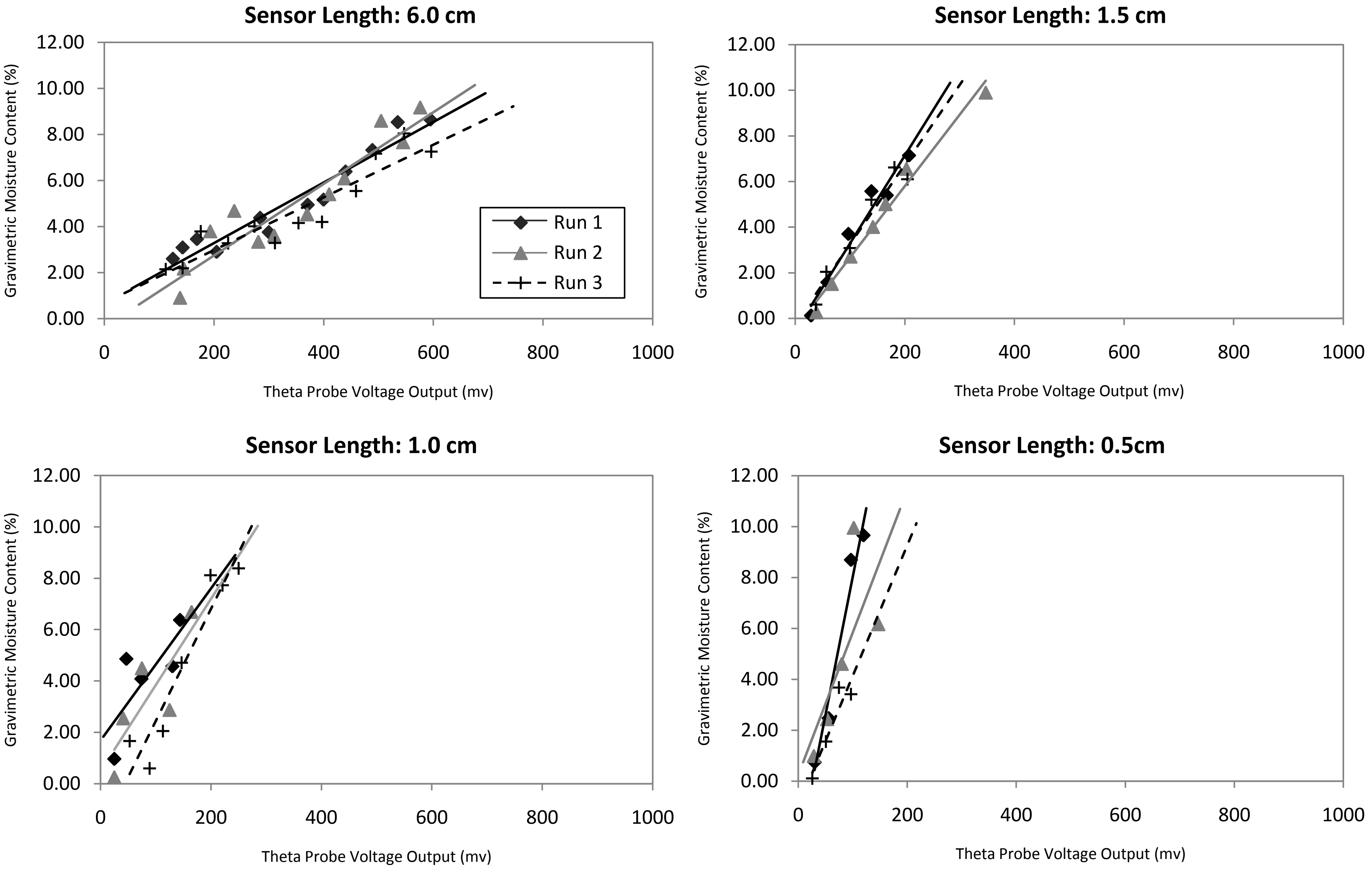
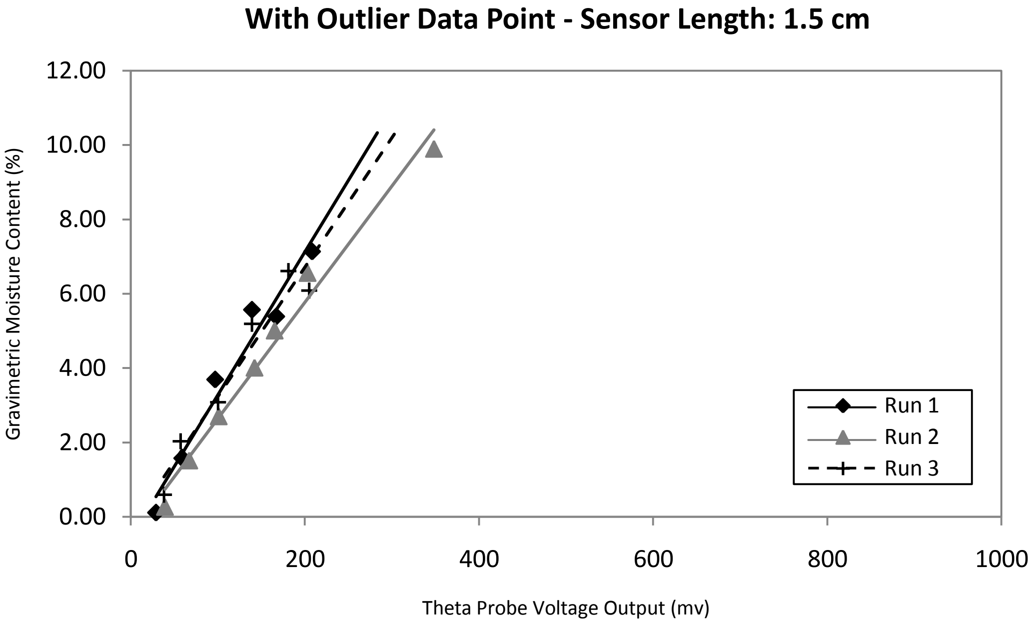


Figure 6.8: Calibration relationships for moisture content below 10 % (gravimetric) at sensor lengths of 6.0, 1.5, 1.0 and 0.5 cm for Kill Devil Hills, North Carolina illustrating repeatability.

Additionally, the 1.5 cm sensor length has excellent repeatability below moisture content values of approximately 7% (gravimetric). As with the 6.0 cm sensor length, there is an increase in the variance between the calibrations above this value. For the 1.0 and 0.5 cm sensor lengths there is considerable variance in the calibration relationships. This suggests that the repeatability of the Theta Probe is poor for the KDH study site at these sensor lengths. The variance in the experimental runs for the 1.5, 1.0 and 0.5 sensor rod lengths can be explained by outliers in the data set of the experimental runs. Eliminating these data points greatly improved the repeatability between experimental runs for each sensor length (Figures 5.8, 5.9 and 5.10). This insinuates that the variance in the calibrations is due to outliers in the data set rather than from the Theta Probe itself, and that the interchangeability of the Theta Probe is considerably higher than initially believed.

Interesting, is the repeatability between the calibration relationships diminishes with a decrease in the sensor length, illustrated by the increase in standard deviation as sensor rod length decreases for both study site particularly the two shortest sensor lengths (Table 5.7). This finding may be misleading as the number of moisture samples used to compose the data becomes smaller with a decrease in sensor rod length. As illustrated in section 5.1.1, when a data set is composed of a small number of samples outliers within the data set can magnify error. Figure 5.11 depicts an increase in standard error of the calibration slopes with a decrease in the average number of moisture samples per experimental run for both study sites. This indicates that the number of moisture samples used during analysis can influence the repeatable variance of the Theta Probe.

Initial investigation of the repeatability of the Theta Probe revealed multiple sensor lengths with poor repeatability, suggesting that the Theta Probe has a very low level



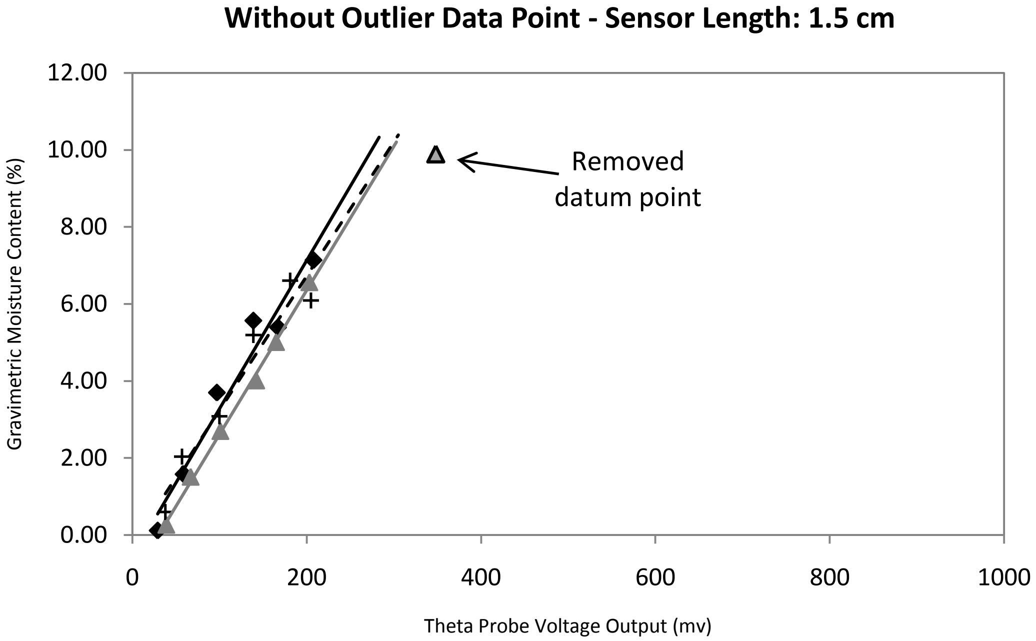
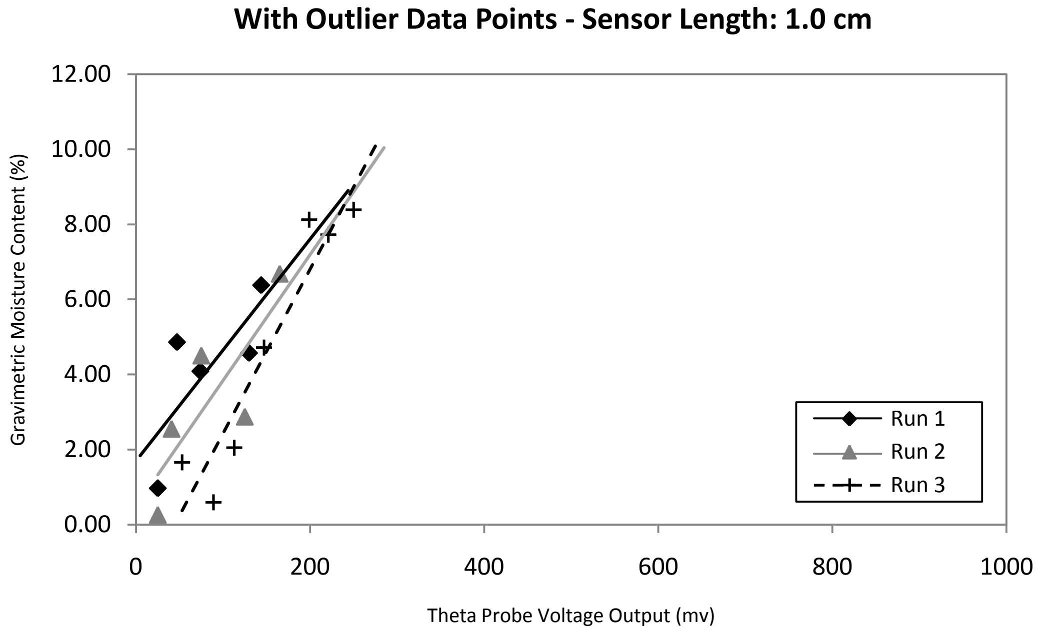


Figure 5.8: Illustration of improvement in repeatability at the 1.5 cm sensor length as outlier data point is removed from experimental run 2 data set for the KDH study site.


With Outlier Data Points - Sensor Length: 1.0 cm

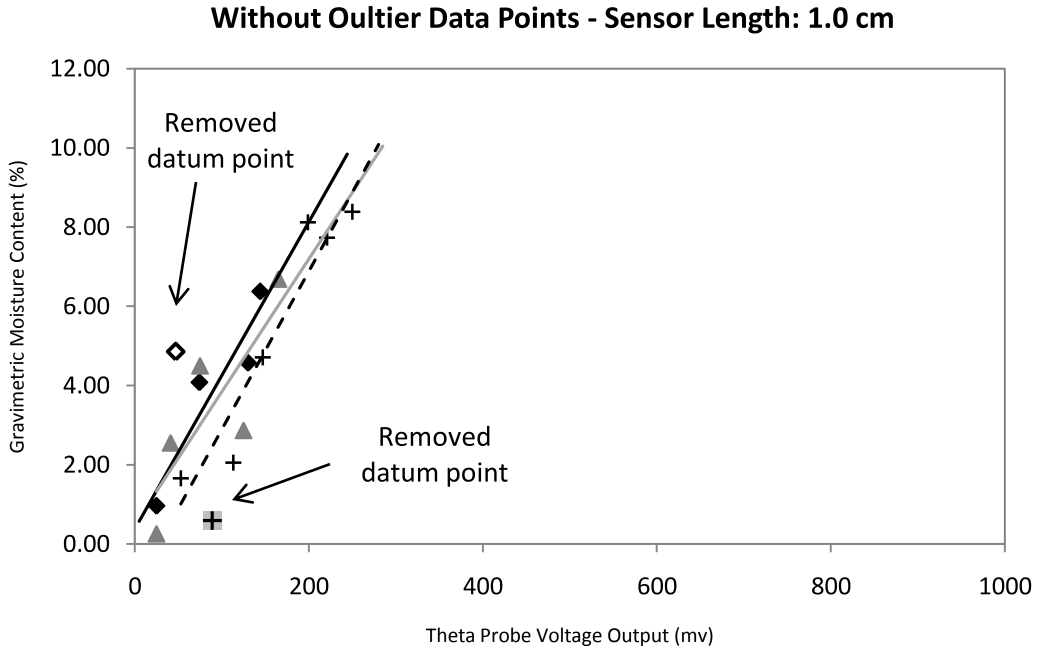
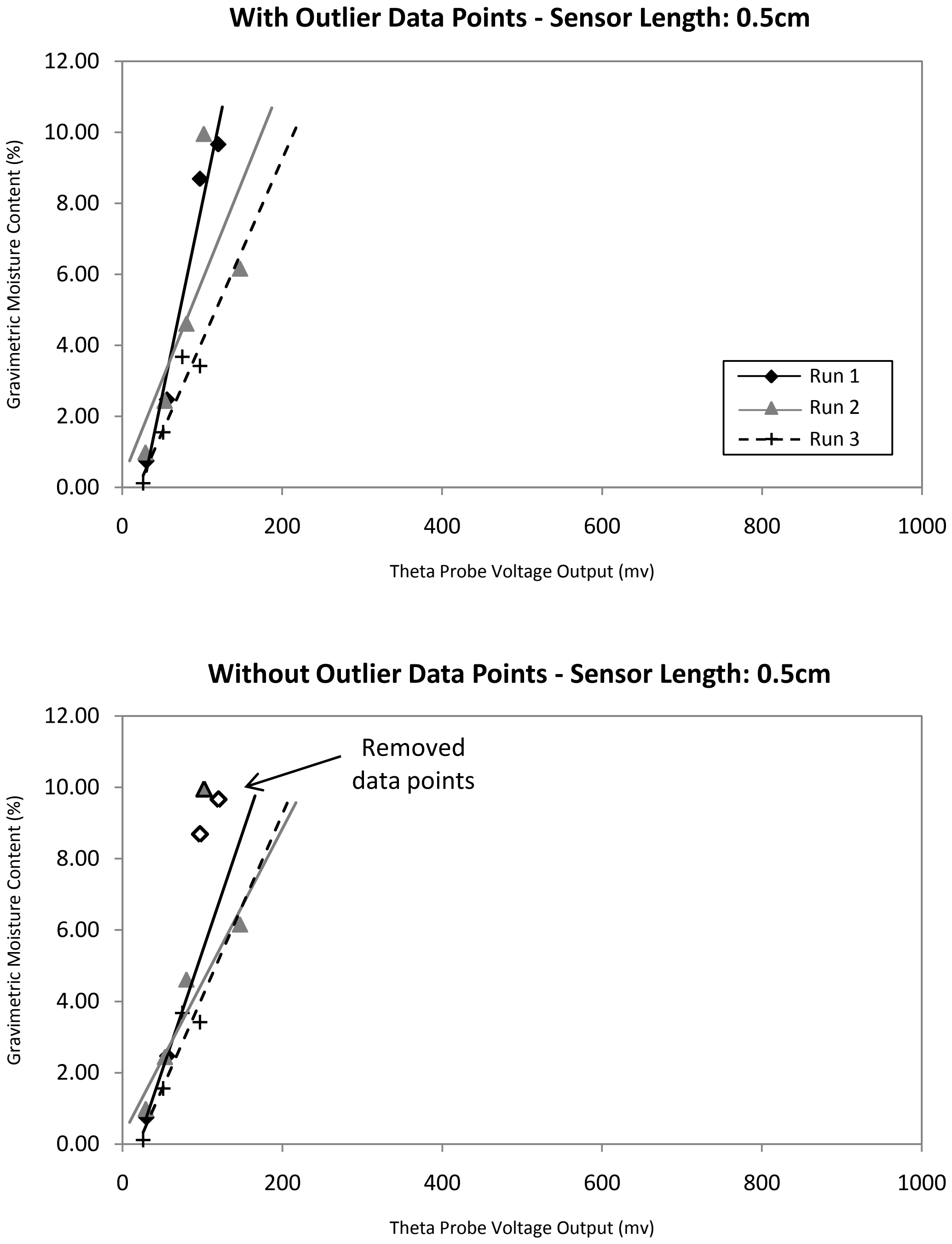

Without Oultier Data Points - Sensor Length: 1.0 cm

Figure 5.9: Illustration of improvement in repeatability at the 1.0 cm sensor length as outlier data points are removed from experimental runs 1 and 3 data sets for the KDH study site.



With Outlier Data Points - Sensor Length: 0.5cm

Without Outlier Data Points - Sensor Length: 0.5cm

Figure 5.10: Illustration of improvement in repeatability at the 0.5 cm sensor length as outlier are data points are removed from experimental runs 1 and 2 data sets for KDH study site.

Table 5.7: Calibration slopes for Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, TX

Sensor Length (cm)	Experimental Run			Mean Slope	Std. Deviation
	1	2	3		
6.0	0.017	0.012	0.015	0.015	0.003
1.5	0.014	0.015	0.015	0.015	0.001
1.0	0.050	0.038	0.025	0.038	0.013
0.5	0.052	0.040	0.025	0.039	0.014

Kill Devil Hills, NC

Sensor Length (cm)	Experimental Run			Mean Slope	Std. Deviation
	1	2	3		
6.0	0.013	0.015	0.011	0.013	0.002
1.5	0.038	0.031	0.034	0.034	0.004
1.0	0.029	0.033	0.043	0.035	0.007
0.5	0.110	0.055	0.051	0.072	0.033

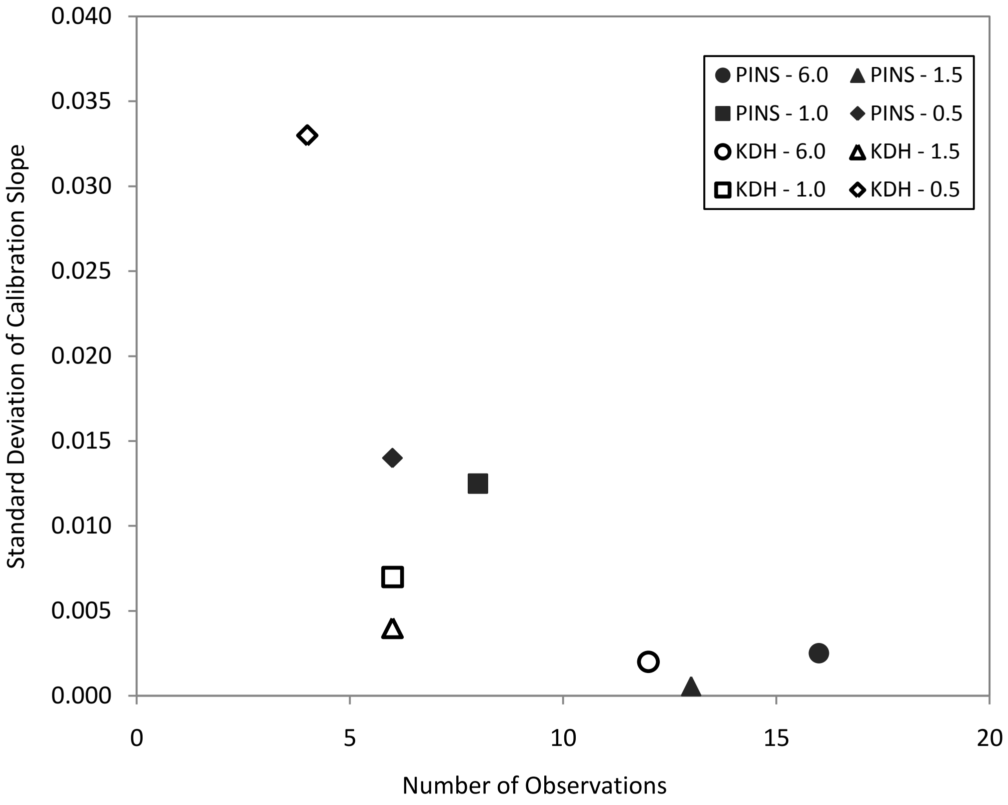


Figure 5.11: Comparison between the standard deviation of the calibration slopes and the average number of observations per experimental run per sensor length.

repeatability. However, a large portion of this variance could be explained by outliers in the data sets. This indicates that the repeatability of the Theta Probe for moisture contents less than 10% is actually very strong. Furthermore, it was found that the repeatability of the Theta Probe is greatly influenced by the number of samples per data set.

5.1.4 Interchangeability

Figures 5.12 and 5.13 depict the variability in the calibrations for experimental run one conducted for probe A and probe B for both study sites. For the PINS study site the interchangeability of the Theta Probe appears very poor, particularly at the 6.0, 1.5 and 1.0 cm sensor lengths. At the 6.0 cm sensor length, the interchangeability is very poor at low moisture contents. Below moisture content values of 2% (gravimetric) there is a greater than 2% (gravimetric) difference in moisture content between the calibrations for probes A and B. This suggests that the probe has a low degree of interchangeability at low moisture content values. At the 1.5 and 1.0 cm sensor lengths, the interchangeability between the calibrations is very poor at high moisture content values. There is a greater than 2% (gravimetric) difference in moisture content values between the calibration relationships for probe A and B above moisture content values of 8% (gravimetric). The 0.5 cm sensor length depicts excellent interchangeability. There is a difference in moisture content on average of less than 0.5% (gravimetric) between the calibrations from probe A and B.

For the KDH study site the interchangeability at the 6.0 and 1.5 cm sensor lengths is excellent. The calibration relationships for both sensor lengths have no greater than a 0.8% (gravimetric) difference in moisture content values. The interchangeability at the 1.0 and 0.5 cm sensor lengths are slightly less in strength than at the 6.0 and 1.5 cm lengths. At the 1.0 cm sensor length there is nearly a 2% (gravimetric) difference between the calibrations at very low moisture contents. The difference between the calibration relationships for probes A and B at the 0.5 cm sensor length are dramatically higher, with as much as a 3% (gravimetric) difference at moisture contents above approximately 7% (gravimetric).

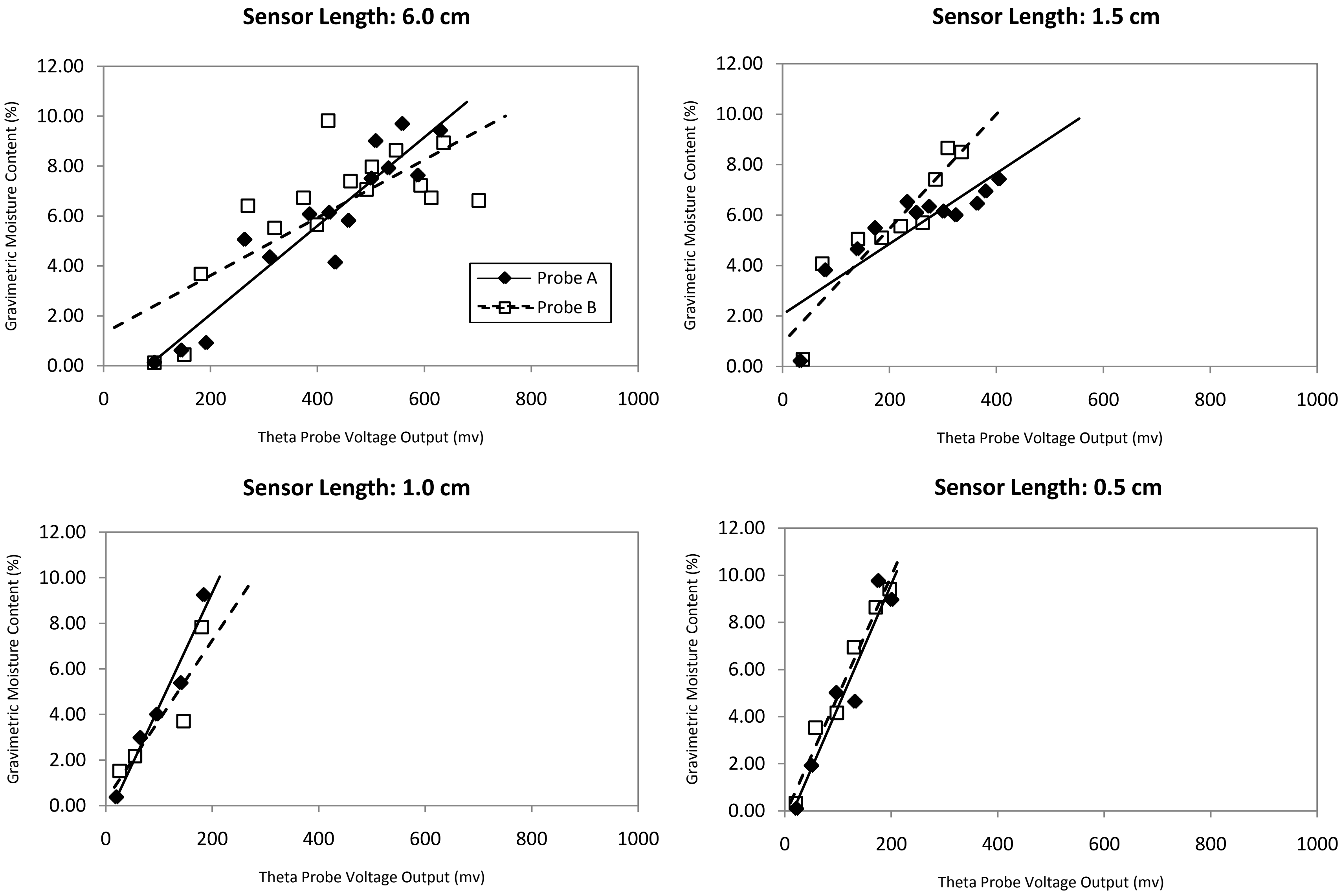
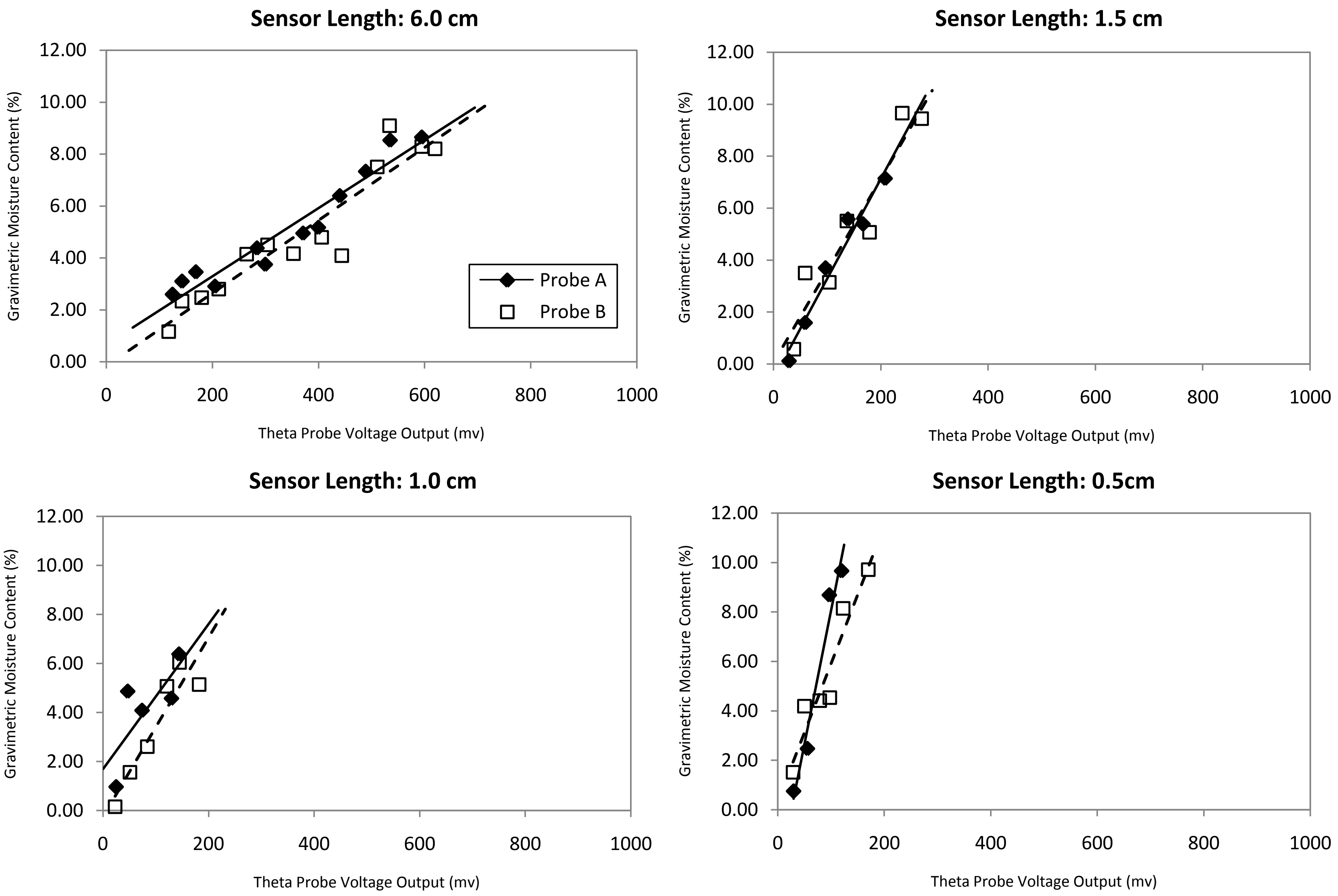


Figure 5.12: Calibration relationships for moisture content below 10 % (gravimetric) at sensor lengths of 6.0, 1.5, 1.0 and 0.5 cm for experimental run 1 using probe A and probe B for Padre Island National Seashore, Texas illustrating interchangeability.


Sensor Length: 6.0 cm

Sensor Length: 1.5 cm

Sensor Length: 1.0 cm

Sensor Length: 0.5cm

Figure 5.13: Calibration relationships for moisture content below 10 % (gravimetric) at sensor lengths of 6.0, 1.5, 1.0 and 0.5 cm for experimental run 1 using probe A and probe B for Kill Devil Hills, North Carolina illustrating interchangeability.

These findings illustrate mixed results on the utility of the Theta Probe to conduct reliable measurements between two different probes. For both study sites there are sensor lengths with good interchangeability and other sensor lengths with poor interchangeability. However, as illustrated in section 5.1.3 of this chapter, the variance between calibrations can be influenced by outliers within the data set. For the PINS study site, elimination of these data points dramatically decreased the interchange variance between the calibrations for probe A and B at the 6.0 and 1.0 cm sensor lengths (Figures 5.14, and 5.15). Removal of the outliers in the data sets, however; did not greatly improve the interchangeability between the calibrations at the 1.5 cm sensor length (Figure 5.16). For the KDH study site, removal of the outliers in the data sets at the 1.0 cm sensor length considerably improved the variance between the calibration relationships for probes A and B (Figure 5.17). However, the interchangeability between the calibrations at the 0.5 cm sensor length did not improve with the removal of the outliers within the data sets (Figure 5.18). These results suggest that the variance in the calibrations is due to outliers in the data set rather than from the Theta Probe itself, and that the interchangeability of the Theta Probe is considerably higher than initially believed.

As with the repeatability, upon first glimpse there were several sensor lengths at both study site locations with very poor interchangeability suggesting that the interchangeability of the Theta Probe is very low. Again however; a large portion of the variance could be explained by outliers in the data sets indicating that the interchangeability of the Theta Probe for moisture contents less than 10% (gravimetric) is much stronger than initially perceived for both study sites.

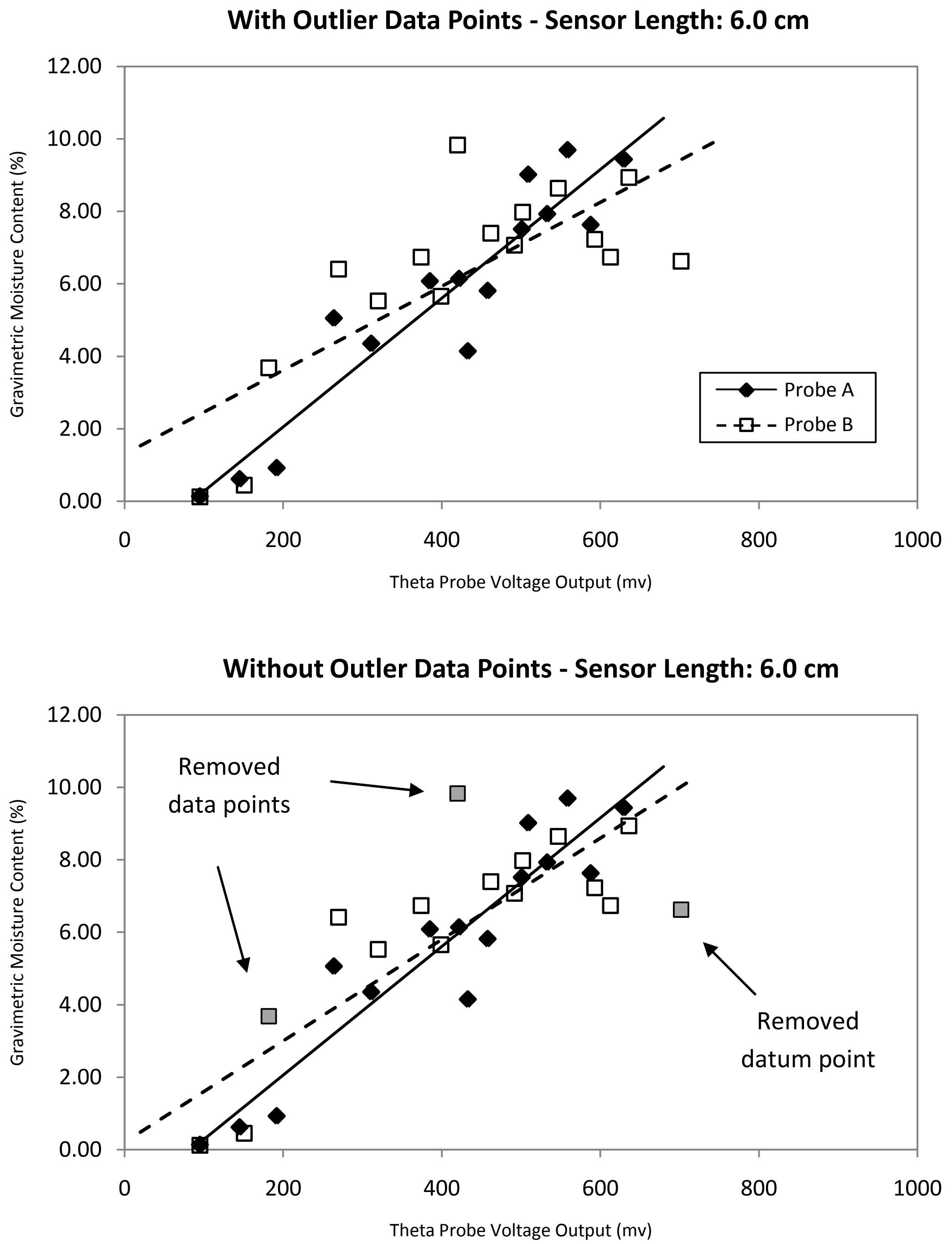
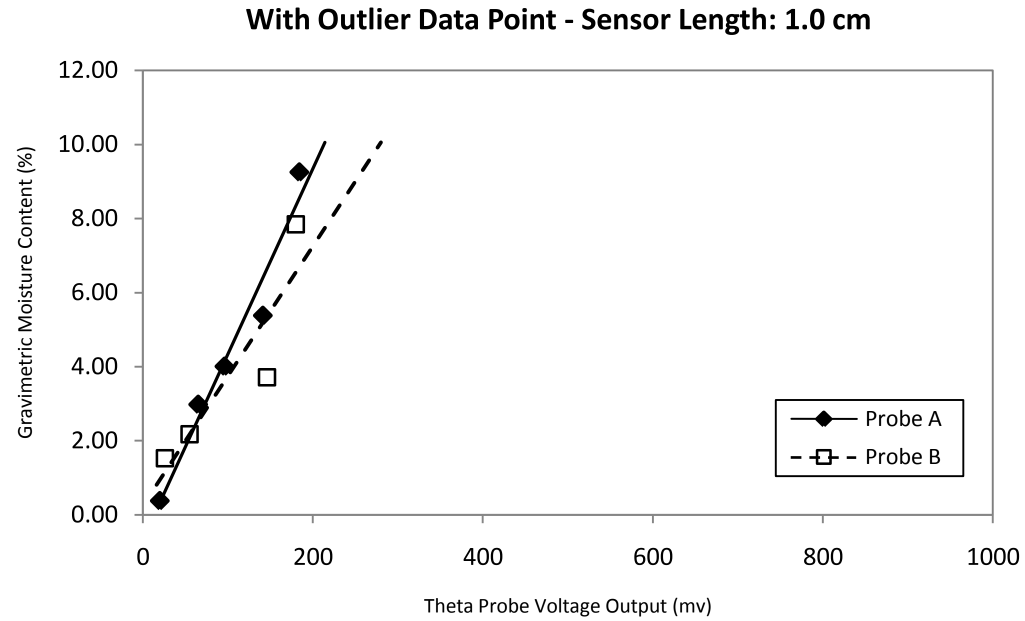


Figure 5.14: Illustration of improvement in interchangeability at the 6.0 cm sensor length as outlier data points are removed from the probe B data set for the PINS study site.



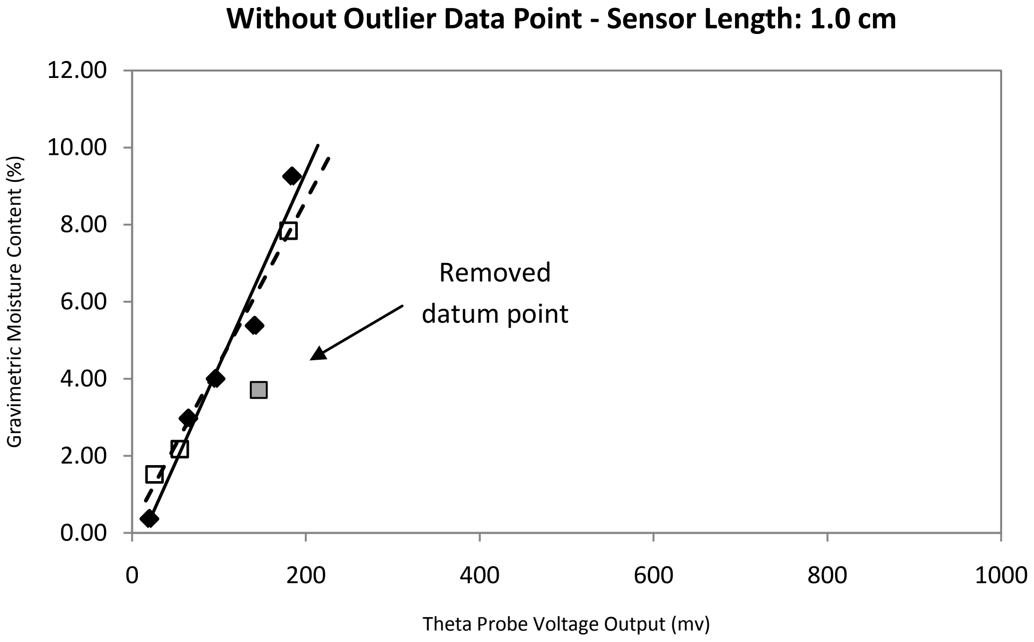
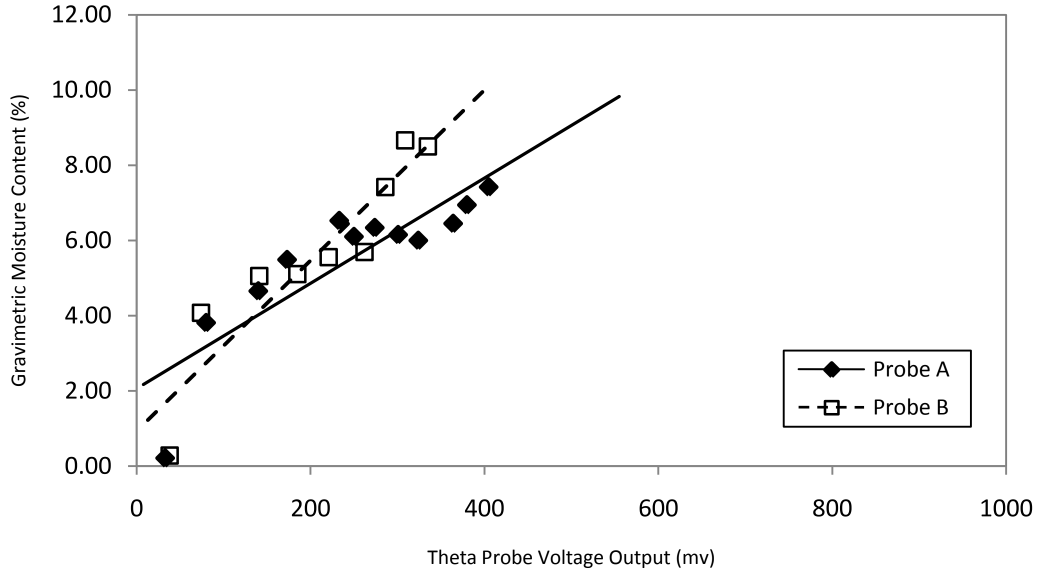


Figure 5.15: Illustration of improvement in interchangeability at the 1.0 cm sensor length as outlier data points are removed from the probe B data set for the PINS study site.

With Outlier Data Points - Sensor Rod Length: 1.5 cm



Without Outlier Data Points - Sensor Length: 1.5 cm

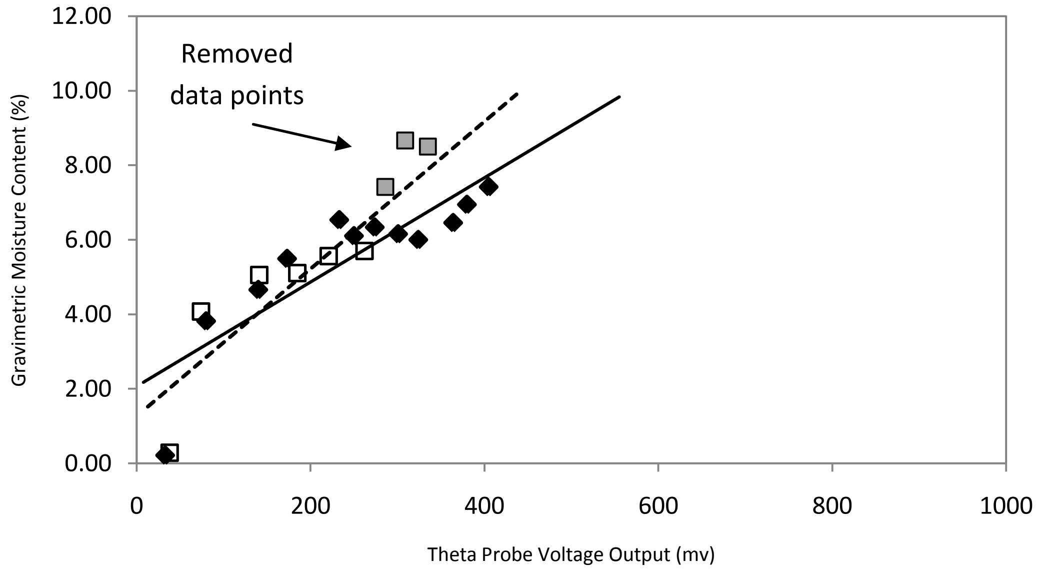
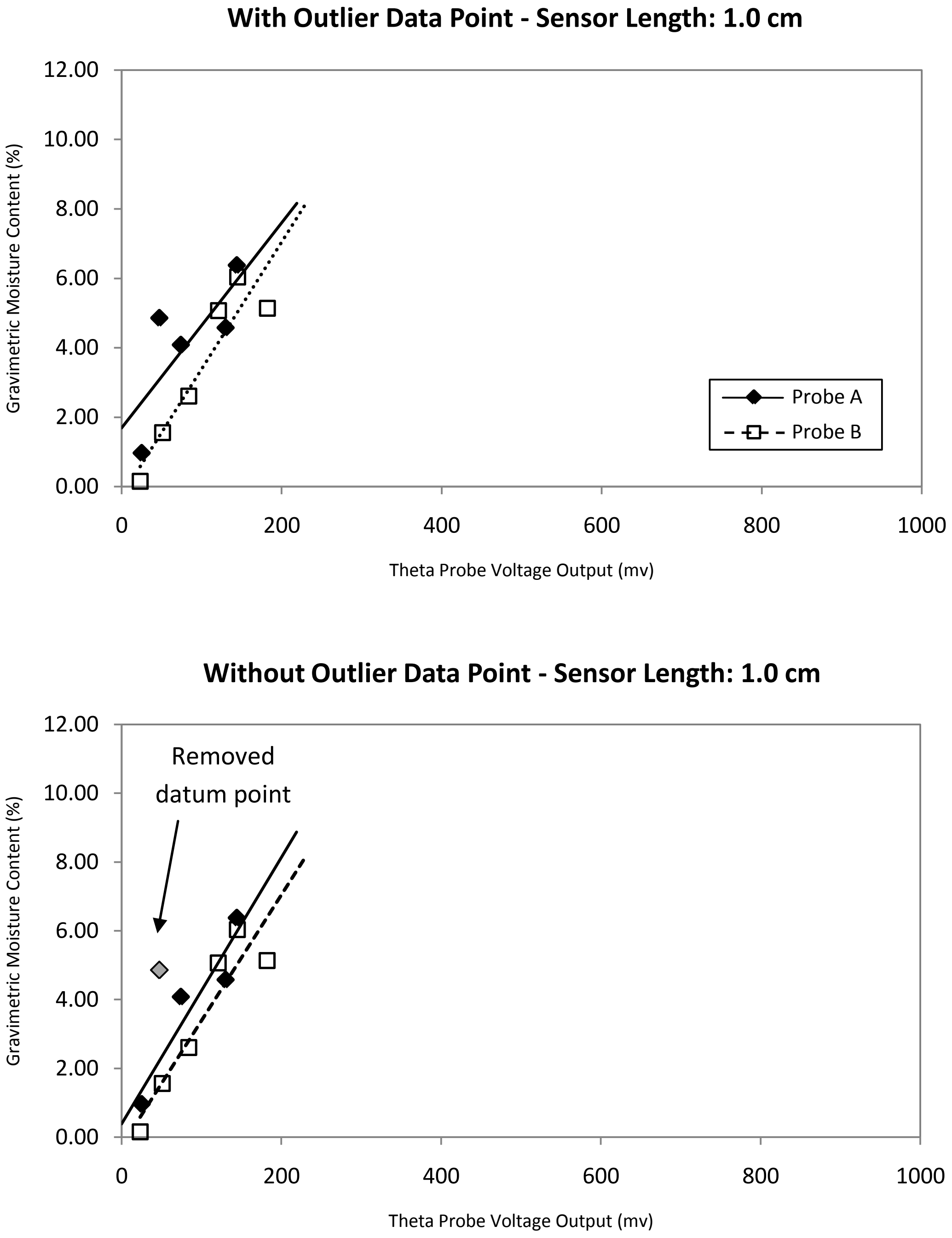


Figure 5.16: Illustration of minimal improvement in interchangeability at the 1.0 cm sensor length as outlier data points are removed from the probe B data set for the PINS study site.



With Outlier Data Point - Sensor Length: 1.0 cm

Without Outlier Data Point - Sensor Length: 1.0 cm

Figure 5.17: Illustration of improvement in interchangeability at the 1.0 cm sensor length as outlier data points are removed from the probe A data set for the PINS study site.

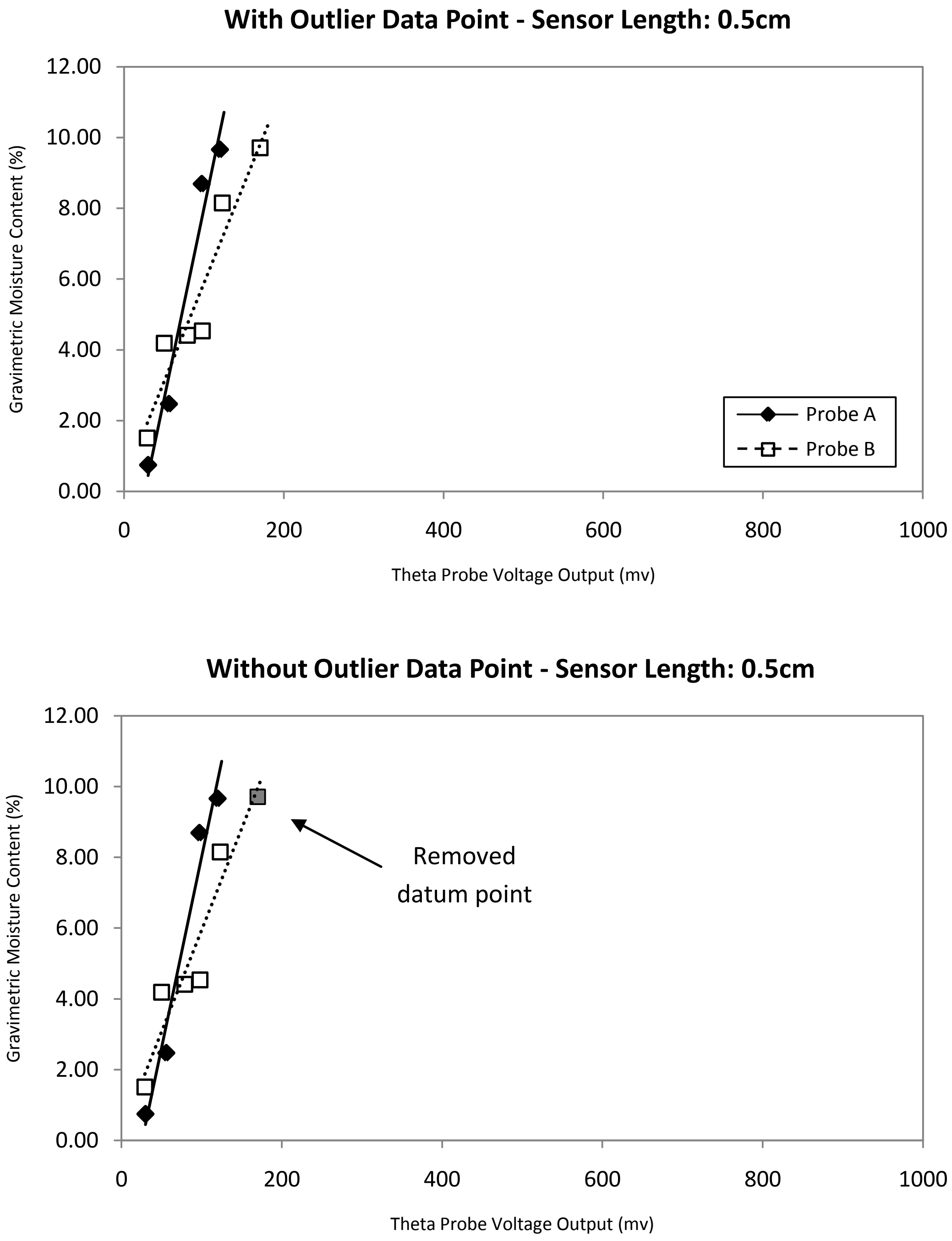


Figure 5.18: Illustration of minimal improvement in interchangeability at the 0.5 cm sensor length as outlier data points are removed from the probe A data set for the PINS study site.

5.2 Summary

This examination revealed several important findings in regard to the utility of the Delta-T Theta Probe for moisture contents less than 10% (gravimetric). First, the length of the sensor rod array significantly affects the slope of the calibration relationship. For both the PINS and KDH study sites the slope of the calibration considerably increases with a decrease in sensor length. The slope of the relationship describes the sensitivity of the probe's response to moisture content, which indicates that sensor length greatly affects the sensitivity of the probe. Therefore, the sensitivity of the probe becomes less pronounced as the length of the sensor rod array shortens. In addition, R^2 values for both study sites indicate strong calibration relationships. There is no consistent reduction in R^2 values as sensor length is decreased indicating that sensor length does not have any demonstrable effect on the strength of the calibration relationship. Relationship strength does become more variable, however; at the two shortest sensor lengths. This variability can be explained by the number of samples per data set, where at sample populations below 5 there is increased scatter in R^2 values ranging from values of 0.97 to values well below 0.70. Furthermore, there is no consistent reduction in SE values as sensor rod length is decreased at either study site. SE values for both study sites are quite close to the manufacturer's rated accuracy of the Theta Probe itself of ±0.7% (gravimetric). This suggests that error in the calibrations is a consequence of error built into the Theta Probe itself and not a result of the shortening of the sensor rod array. Second, an analysis of variance test determined there to be no statistical difference at the 95% confidence interval in the calibration slopes and R^2 values between grain sizes at the 6.0, 1.0, and 0.5 cm sensor lengths. However, the calibration slopes and R^2 values at the 1.5 cm sensor length do differ significantly at the 95% confidence interval. There is no obvious explanation for the variance in the calibration slopes and R^2 values at the 1.5 cm sensor length. Aside from the findings at the 1.5 cm sensor length, these results indicate that sediment size does not influence the sensitivity or strength of the relationship for the Theta Probe. Sediment grain size does, however; influence the accuracy of the Theta Probe. In general, medium sediment is associated with a higher level of accuracy than fine sediment. Finally, initial investigation into the level of repeatability and interchangeability of the Theta Probe revealed mixed results for both study site locations. For both the PINS and KDH study sites there were multiple sensor lengths with very poor repeatability and interchangeability between the calibrations. Nevertheless, a large portion of this variance could be explained by either outliers in the data sets or by operator error in the field or lab. Additionally, it was found that when an experimental run was conducted on the morning after the other experimental run/s were conducted for that sensor length the experimental run produced markedly lower moisture contents. This again brings into question the influence of differing environmental conditions, such as soil temperature (Kaleita et al., 2005a), sediment compaction by wave or aeolian transport, humidity, or salinity.

Chapter 6

Evaluation of Manufacturer Calibration Methods

This chapter will examine the manufacturer's generalized calibration and soil-specific calibration methods. First, the manufacturer's generalized linear and third-order polynomial calibration relationships will be assessed. An evaluation of the manufacturer's generalized calibration relationship will provide an outlook into the accuracy of the calibration method. Finally, the manufacturer's two-point soil-specific calibration method will be discussed.

6.1 Manufacturer Generalized Calibration Method

As previously discussed in chapter 2.2, Delta-T Devices, Ltd. (1999) established the calibration relationship between volumetric water content (θ_v) and Theta Probe voltage output (V) for the Delta-T Theta Probe to be:

$$\theta_v = \frac{[4.44V+1.10]-a_0}{a_1} \tag{6.1}$$

and

$$\theta_v = \frac{[4.70V^3-6.40V^2+6.40V+1.071.07+6.4V]-a_0}{a_1} \tag{6.2}$$

for linear and third-order polynomial relationship where the coefficients a_0 and a_1 are representative of the soil structure and are suggested to have values of 1.6 and 8.4, respectively, for a mineral soil. The reported accuracy of this calibration method by the manufacturer is ± 5.0 % volumetric moisture content (Delta-T Devices, Ltd., 1999), which is approximately 3.5% gravimetric moisture content for the sediments in this study. Conversions of volumetric moisture content (θ_v) to gravimetric moisture content (θ_g) were calculated by:

$$\theta_g = \theta_v \left(\frac{\rho_w}{\rho_s}\right) \tag{6.3}$$

where ρ_w is the density of water (typically 1), and ρ_s is the soil bulk density (Equation 6.4).

$$\rho_s = \frac{M_s}{V_s} \tag{6.4}$$

where M_s is the total mass of dry sample, and V_s is the total volume of soil sample.

Figures 6.1 and 6.2 are plots of the laboratory-measured moisture contents (% gravimetric) versus moisture content values (% gravimetric) predicted from the manufacturers generalized calibrations for the PINS and KDH study sites at the 6.0 cm sensor length. The manufacturer's generalized linear and third-order calibration relationships consistently overestimate the moisture content values for every experimental run at both study site locations.

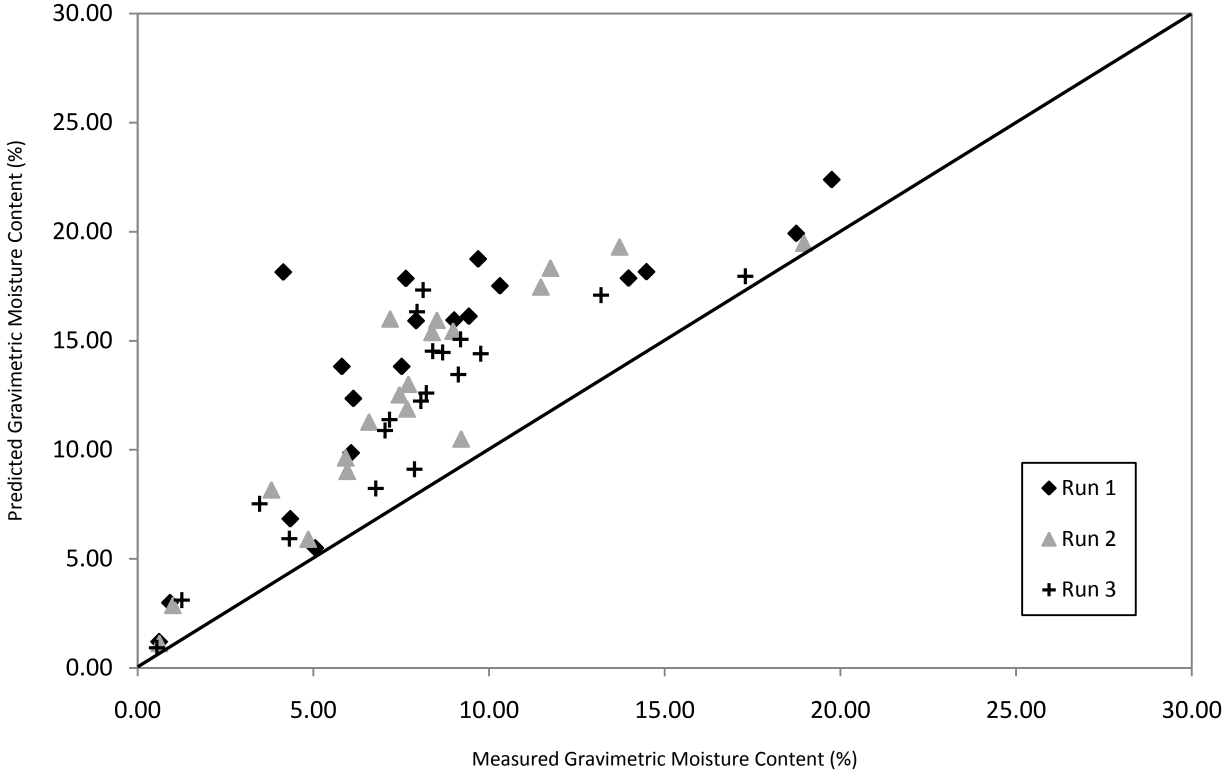
To quantify the level of error associated with using the manufacturer's generalized calibration, the root mean square error (RMSE) was calculated. The RMSE for this analysis is calculated as:

$$RMSE = \sqrt{\frac{1}{n}\sum\left(\theta_{measured} - \theta_{gc}\right)^2} \tag{6.5}$$

where $\theta_{measured}$ is the laboratory determined gravimetric moisture content from a field moisture sediment sample, θ_{gc} is the gravimetric moisture content determined from the manufacturer's calibration values, and n is the total number of samples (Cosh et al., 2005). Results are presented in Table 6.1. Mean RMSE values for the linear and third-order polynomial relationships are 5.2% and 4.8% (gravimetric), respectively, for the PINS site and 6.7% and 6.3% (gravimetric), respectively, for the KDH site. The actual error in the predicted values is thus about 50-100% larger than the manufacturer-estimated accuracy of approximately 3.5% (gravimetric).

These findings agree with Cosh et al. (2005) and Kaleita et al. (2005), in which they both found the manufacturer's generalized calibration relationship to overestimate the moisture content values. This indicates that the suggested values of 1.6 and 8.4 for the coefficients a_0 and a_1 are not accurate representations of all types of mineral soil, particularly for beach sand.

Manufacturer's Generalized Calibration - Linear



Manufacturer's Generalized Calibration – Third-Order Polynomial

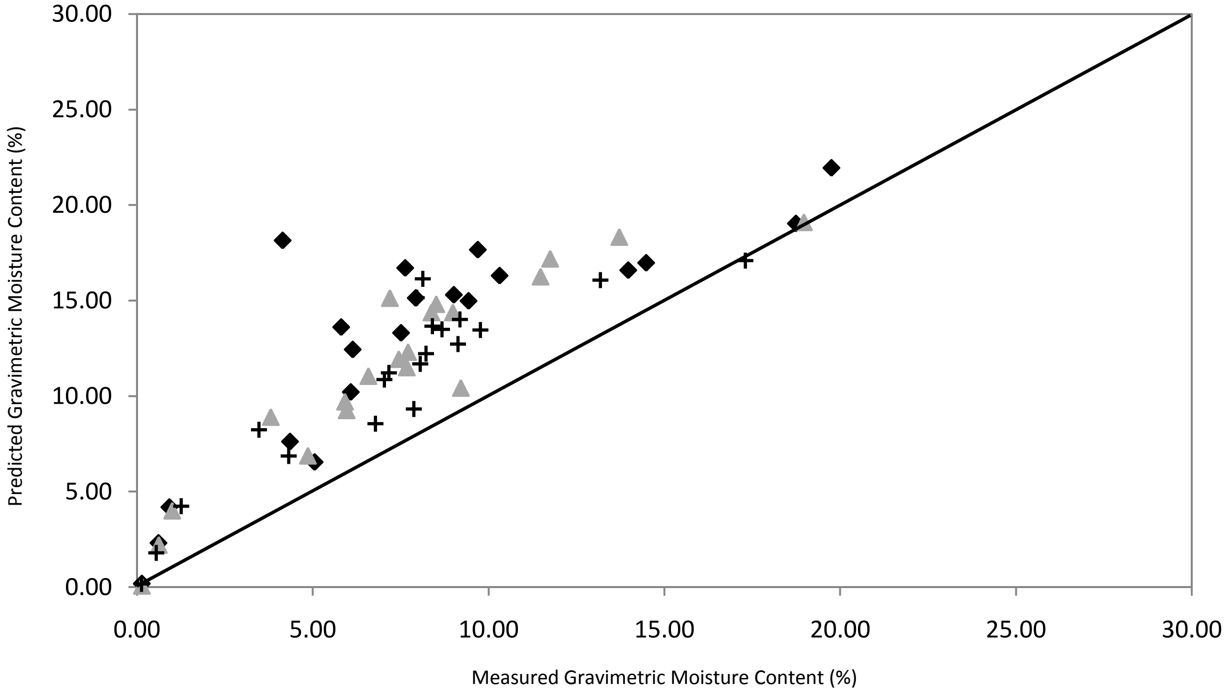
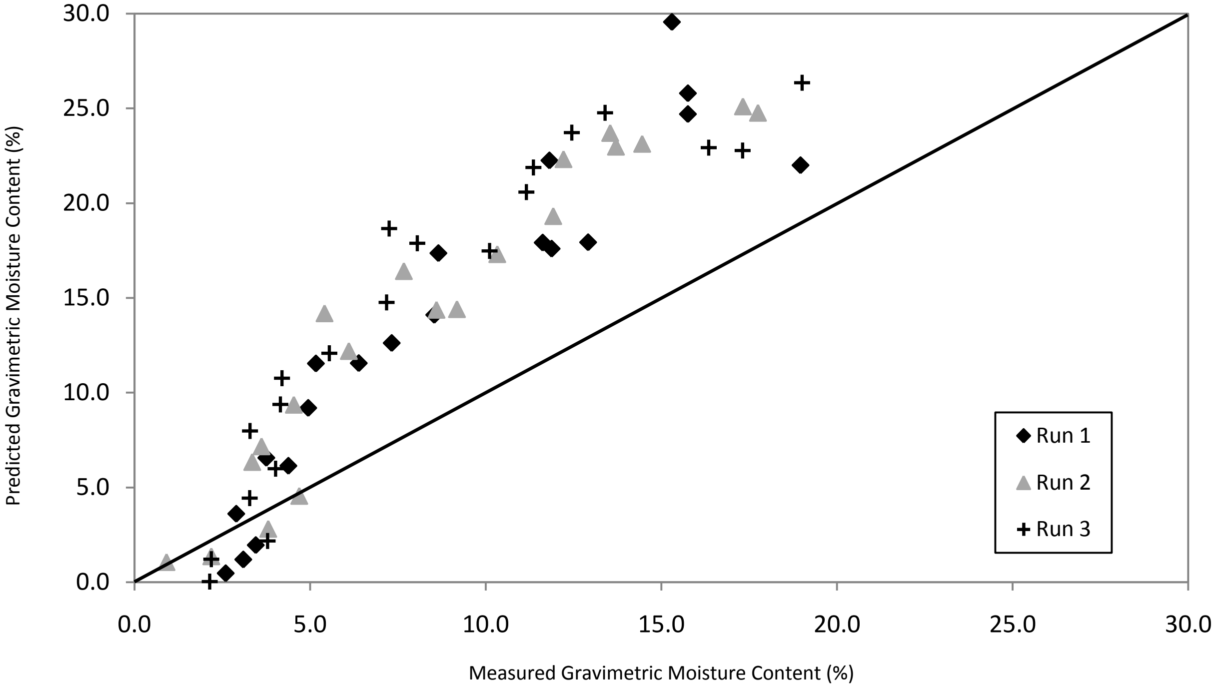
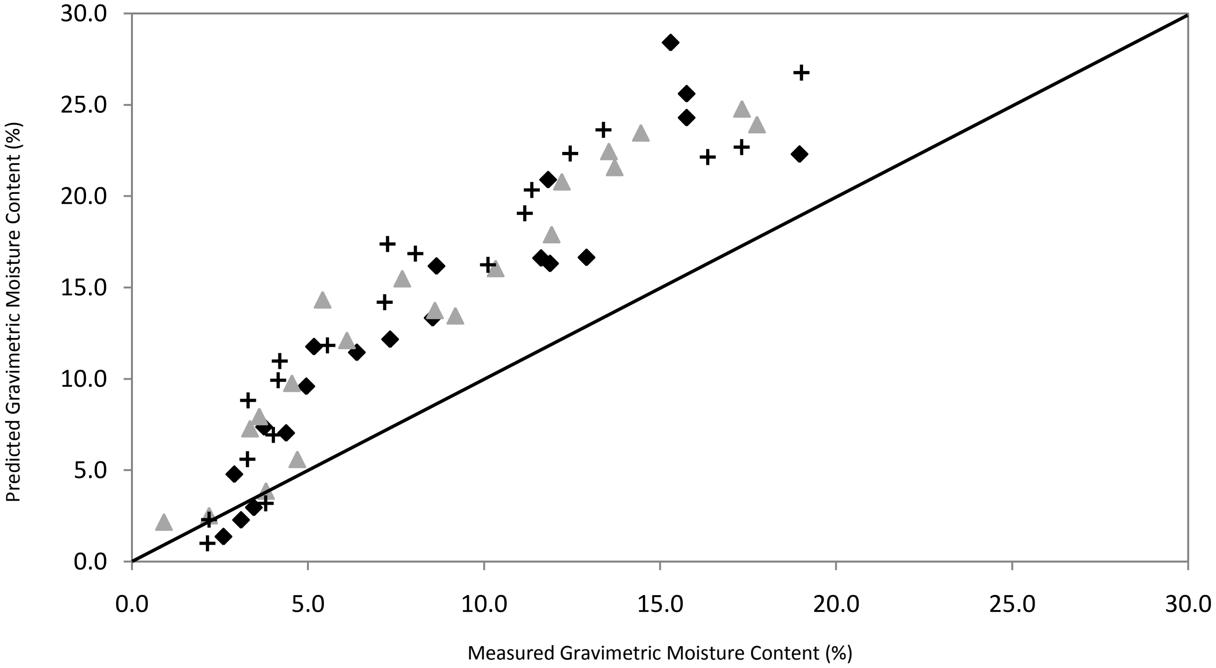


Figure 6.1: Manufacturer's generalized calibration predictions versus field measurements (% gravimetric) for Padre Island National Seashore, Texas.



Manufacturer's Generalized Calibration - Linear



Manufacturer's Generalized Calibration – Third-Order Polynomial

Figure 6.2: Manufacturer's generalized calibration predictions versus field measurements (% gravimetric) for Kill Devil Hill, North Carolina.

Table 6.1: RMSE values (% gravimetric) for the manufacturer's generalized linear and third-order calibration relationships for the Padre Island National Seashore and Kill Devil Hills study sites.

Padre Island National Seashore, TX

Calibration Equation	Experimental Run 1	2	3	Mean
3rd order	5.9	4.4	4.1	4.8
Linear	6.3	4.9	4.5	5.2

Kill Devil Hills, NC

Calibration Equation	Experimental Run 1	2	3	Mean
3rd order	6.0	6.1	6.7	6.3
Linear	6.5	6.4	7.3	6.7

The clear overestimation of moisture contents by the manufacturer's generalized calibration relationships leads to the need for a method to quantify more appropriate a_0 and a_1 values. The manufacturer provides a soil-specific method that allows the researcher to calculate the actual calibration coefficient values for the particular soil of interest. This approach will be investigated next.

6.2 Manufacturer Recommended Soil-Specific Calibration Method

The manufacturer's soil-specific calibration method uses a two-point approach to calculate the coefficients a_0 and a_1. The method requires a voltage output reading for an initially moist sample, which is then oven-dried and a second voltage output reading is taken for the dry sample. The calibration coefficients a_1 and a_0 are then calculated from the wet and dry voltage output readings (Delta-T Devices, Ltd., 1999).

There is a crucial shortcoming to this calibration method for sand. The calibration coefficient a_0 is calculated from the voltage output reading for the dried sample; taking a voltage output reading from a dried sample is particularly difficult for beach sand, which contracts and becomes fragile upon drying (Kaleita et al., 2005). Insertion of the sensor rods into the dried sample will almost always rupture inter-grain connections to an extent that the soil structure, packing, etc. are substantially disrupted. This disruption will in turn influence the voltage output for that sample. This shortcoming renders the manufacturer's soil-specific calibration method impractical for beach sand; hence, it was not attempted here.

6.3 Summary

The manufacturer's generalized linear and third-order calibration relationships consistently overestimate the moisture content values for every experimental run at both study site locations. The RMSE error for the generalized calibration relationships are approximately 50-100% larger than the manufacturer-estimated accuracy of approximately 3.5% (gravimetric). This suggests that the values of 1.6 and 8.4 for the coefficients a_0 and a_1 are not accurate representations of beach sand. Furthermore, a serious shortcoming in the manufacturer's soil-specific calibration method renders it impractical for beach sand; as insertion of sensor rods into a dried sample ruptures the soil structure, packing, etc., which influences the voltage output for that sample.

Chapter 7

Conclusions

There are several conclusions that can be drawn from the data that has been presented here:

1) A third-order polynomial relationship produces a stronger and more accurate assessment of the utility of the Delta-T Theta Probe to conduct surface moisture measurements than a linear calibration relationship. Results showed vastly improved R^2 and SE values for the third-order calibration function compared to the linear calibration function.

2) Overall, the utility of the Theta Probe is very high as the length of the sensor rod array is shortened. Results from the analyses of the full moisture range and moisture contents less than 10% indicate that the sensor rod array does not have any significant influence on the strength of the Theta Probe. For both analyses, there was no consistent reduction in R^2 values. In fact, for every experimental run one or more of the experimental runs with a shortened-probe showed a larger or equal R^2 value than the full 6.0 cm probe length. This signifies that the Theta Probe is capable of producing very strong calibration relationships at shallow measurements lengths. Second, analysis of the full moisture range determined there to be a slight reduction in accuracy as sensor length is decreased. Furthermore, the SE values for each experimental run at both study sites fell below the associated accuracy range of approximately 3.5% (gravimetric) established by the manufacturer as well as within accuracy ratings illustrated by the literature. These results compare favorably with the analysis of moisture contents less than 10%, which found there to be no consistent reduction in accuracy as sensor length is decreased. This indicates that the Theta Probe is very reliable as the length of the sensor rod array is shortened for both the full moisture content range and moisture contents less than 10%. Third, the sensor rod length has an astounding influence on the sensitivity of the Theta Probe. At lower moisture

contents the sensitivity of the probe weakens as the sensor length decreases, whereas, at higher moisture contents, typically greater than 15%, the sensitivity of the probe becomes stronger as sensor rod length decreases.

3) Analysis of the full moisture content range revealed that sediment grain size has a notable influence on the sensitivity of the Theta Probe. Fine sediment has a more pronounced sensitivity than medium sediment. Additionally, grain size does not influence the strength or accuracy of the Theta Probe. R^2 and SE values were found to have no statistical difference between grain sizes.

These findings contradict the findings of the analysis for moisture contents less than 10%. When analyzing moisture content less than 10% (gravimetric), it was determined that sediment grain size does not have any influence on the sensitivity of the Theta Probe at sensor lengths of 6.0, 1.0 and 0.5 cm. Grain size only had a significant influence on the sensitivity of the probe at the 1.5 cm sensor length. Additionally, SE values indicate that sediment grain size has an influence on the accuracy of the Theta Probe. In general, medium sediment is associated with a higher level of accuracy than fine sediment. A probable explanation for these discrepancies is that at the full moisture content range data points higher than 10% moisture content are altering the calibrations, which would not be evident when analyzing moisture content less than 10%.

4) Initial investigation into the repeatability and interchangeability of the Theta Probe produced mixed results regarding the probe utility to conduct replicatable measurements either with a single probe or two different probes for both analyses. For the PINS and KDH study sites there were multiple sensor lengths with very poor repeatability and/or interchangeability between the calibrations. Nevertheless, a large portion of the variance between the calibrations could be explained by outliers in the data sets, which may be due to operator error in the field or lab. This

suggests that the repeatability and interchangeability is much greater than initially perceived, indicating that overall the Delta-T Theta Probe is very reliable to conduct repeatable measurements with a single probe and between two different probes. An interesting result occurred when an experimental run was conducted on a different day than that of the other experimental run/s at that sensor length. The experimental run produced consistently lower moisture content values. Possible explanations for this could due to differing environmental conditions, such as soil temperature (Kaleita et al., 2005a), sediment compaction by wave or aeolian transport, humidity, or salinity. Each of these are possible explanations as more research is needed to identify the influence that each of these may have on the calibrations.

5) The Manufacturer's generalized linear and third-order calibration relationships consistently overestimate the moisture content values for all experimental runs at both study site locations. The RMSE error for the generalized calibration relationships are approximately 50-100% larger than the manufacturer-estimated accuracy of approximately 3.5% (gravimetric). This suggests that the values of 1.6 and 8.4 for the coefficients a_0 and a_1 are not accurate representations of beach sand. Furthermore, a serious shortcoming in the manufacturer's soil-specific calibration method renders it impractical for beach sand; as insertion of sensor rods into a dried sample ruptures the soil structure, packing, etc., which influences the voltage output for that sample.

References

Abu-Hamdeh, N.H., 2003. Thermal properties of soils as affected by density and water content. *Biosystems Engineering*, 86(1): 97-102.

Atherton, R.J., Baird, A.J., and Wiggs, G.F.S., 2001. Inter-tidal dynamics of surface moisture content on a meso-tidal beach. *Journal of Coastal Research*, 17(2): 482-489.

Bell, J.P., Dean, T.J., and Hodnett, M.G., 1987. Soil moisture measurement by an improved capacitance technique, Part II: Field techniques, evaluation and calibration. *Journal of Hydrology*, 93: 79-90.

Colombini I., F.M., Chelazzi, L., 2005. Micro-scale distribution of some arthropods inhabiting a Mediterranean sandy beach in relation to environmental parameters. *Acta Oecologica*, 28: 249-265.

Cornelis, W.M., and Gabriels, D., 2003. The effect of surface moisture on the entrainment of dune sand by wind: an evaluation of selected models. *Sedimentology*, 50: 771-790.

Cosh, M.H., Jackson, T.J., Bindlish, R., Famiglietti, J.S., and Ryu, D., 2005. Calibration of an impedance probe for estimation of surface soil water content over large areas. *Journal of Hydrology*, 311: 49-58.

Dean, T.J., Bell, J.P., and Baty, A.J.B., 1987. Soil moisture measurement by an improved capacitance technique, Part I: Sensor design and performance. *Journal of Hydrology*, 93: 67-78.

Delta-T Devices., 1999. *Theta Probe Soil Moisture Sensor Type ML2x User Manual*. Cambridge, United Kingdom: Delta-T Devices, Ltd.

Delta-T Devices., 2005. *Moisture Meter Type HH2 User Manual*. Cambridge, United Kingdom: Delta-T Devices, Ltd.

Fares, A., and Polyakov, V., 2006. Advances in crop water management using capacitive water sensors. *Advances in Agronomy*, 90: 43-77.

Gaskin, G.J., and Miller, J.D., 1996. Measurement of soil water content using a simplified impedance measuring technique. *Journal of Agricultural Engineering Research*, 63: 153-160.

Hank, R.J., 1992. *Applied Soil Physics: Soil Water and Temperature Applications*. Spinger-Verlag, New York.

Harnett, D.L., 1975. *Introduction to Statistical Methods*. Addison-Wesley Publishing Company, Reading, Massachusetts.

Hayward, S.A.L., Worland, M.R., Convey, P., and Bale, J.S., 2004. Habitat moisture availability and the local distribution of the Antarctic Collembola *Cryptopygus antarcticus* and *Friesea grisea*. *Soil Biology and Biochemestry*, 36: 927-934.

Hillel, D., 1971. *Soil and Water: Physical Principles and Processes*. Academic Press, Inc, New York.

Jackson, N.L., and Nordstrom, K.F., 1997. Effects of time-dependent moisture content of surface sediments on aeolian transport rates across a beach, Wildwood, New Jersey, U.S.A. *Earth Surface Processes and Landforms*, 22: 611-621.

Jackson, T.J., Schmugge, J., and Engman, E.T., 1996. Remote Sensing applications to hydrology: soil moisture. *Hydrological Sciences*, 41(4): 517-530.

Kaleita, A.L., Heitman, J.L., and Logsdon, S.D., 2005a. Field calibration of the theta probe for Des Moines lobe soils. *Applied Engineering in Agriculture*, 21(5): 865-870.

Kaleita, A.L., Tian, L.F., and Hirschi, M.C., 2005b. Relationship between soil moisture content and soil surface reflectance. *American Society of Agricultural Engineers*, 48(5): 1979-1986.

McKenna Neuman, C., and Langston, G., 2003. Spatial Analysis of surface moisture content on beaches subject to aeolian transport, Proceedings of the Canadian Coastal Conference, Queen's University, Kingston, Ontario, Canada, pp. 1-10.

McKenna Neuman, C., and Langston, G., 2006. Measurement of water content as a control of particle entrainment by wind. *Earth Surface Processes and Landforms*, 31: 303-317.

Muller, E., and Decamps, H., 2001. Modeling soil moisture - reflectance. *Remote Sensing of Environment*, 76: 173-180.

Mullins, C.E., Mandiringana, O.T., Nisbet, T.R. and Aitken, M.N., 1986. The design, limitation, and use of a portable tensiometer. *Journal of Soil Science*, 37: 691-700.

Namikas, S.L., and Sherman, D.J., 1995. A review of the effects of surface moisture content on aeolian sand transport. In: V.P. Tchakerian (Editor), *Desert Aeolian Processes*. Chapman & Hall, London, pp. 269-293.

National Climatic Data Center (NCDC)., 2007. http://www.ncdc.noaa.gov. January 30, 2007.

National Oceanic and Atmospheric Administration (NOAA)., 2007. *Tides and Currents*. http://www.tidesandcurrents.noaa.gov. January 30, 2007.

Or, D., 2001. Who invented the tensiometer? *Soil Science Society of America Journal*, 65(1): 1-3.

Paltineanu, I.C., and Starr, J.L., 1997. Real-time soil water dynamics Using multisensor capacitance probes: laboratory calibration. *Soil Science Society of America Journal*, 61: 1576-1585.

Richards, L.A., 1942. Soil moisture tensiometer materials and construction. *Soil Science*, 53(4): 241-248.

Robinson, D.A., Gardner, C.M.K., and Cooper, J.D., 1999. Measurement of relative permittivity in sandy soils using TDR, capacitance and theta probes: comparison, including the effects of bulk soil electrical conductivity. *Journal of Hydrology*, 223: 198-211.

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. *Journal of Soil Science*, 43: 1-13.

Sarre, R.D., 1988. Evaluation of aeolian sand transport equations using intertidal zone measurements, Sauton Sands, England. *Sedimentology*, 35: 671-679.

Souza, C.F., and Matsura, E.E., 2003. Multi-wire time domain reflectometery (TDR) probe with electrical impedance discontinuities for measuring water content distribution. *Agricultural Water Management*, 59: 205-216.

Take, W.A., and Bolton, M.D., 2003. Tensiometer saturation and the reliable measurement of soil suction. *Geotechnique*, 53(2): 159-172.

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.

Topp, G.C., and Davis, J.L., 1984. Measurement of soil water content using time-domain reflectometry (TDR): A field evaluation. *Soil Science Society of America Journal*, 49: 19-24.

Tsegaye, T.D., Tadesse, W., Coleman, T.L., Jackson, T.J., and Tewolde, H., 2004. Calibration and modification of impedance probe for near surface soil moisture measurements. *Canadian Journal of Soil Science*, 84: 237-243.

U.S. Army Corps of Engineers,. 2007. *Field Research Facility: Duck, NC.* http://www.frf.usace.army.mil/frf.shtml. January 30, 2007.

Weise, B.R. and White, W.A., 1980. *Padre Island National Seashore: A Guide to the Geology, Natural Environments, and History of a Texas Barrier Island*. Bureau of Economic Geology, Austin, Texas.

Whalley, W.R., 1993. Considerations on the use of time-domain reflectometry (TDR) for measuring soil water content. *Journal of Soil Science*, 44: 1-9.

Wiggs, G.F.S., Baird, A.J., and Atherton, R.J., 2004. The dynamic effects of moisture on the entrainment and transport of sand by wind. *Geomorphology*, 59: 13-30.

Yang, Y., and Davidson-Arnott, R.G.D., 2005. Rapid measurement of surface moisture content on a beach. *Journal of Coastal Research*, 21(3): 447-452.

Appendix A

Moisture Measurement Sediment Samples

Padre Island National Seashore, Texas

Sensor Length 6.0 cm

Experimental Run 1 – Probe A

Wet (g)	Dry (g)	% moisture (gravimetric)	Voltage Output (mv)
117.569	117.411	0.13	95
107.75	107.092	0.61	145
106.224	105.254	0.92	192
109.668	104.391	5.06	264
115.705	110.881	4.35	311
110.207	103.892	6.08	385
99.83	94.056	6.14	422
70.384	67.583	4.14	433
99.653	94.178	5.81	458
112.071	104.239	7.51	501
99.127	90.932	9.01	509
105.297	97.564	7.93	533
94.957	86.565	9.69	559
106.134	98.609	7.63	588
115.924	105.083	10.32	622
128	116.966	9.43	630
125.698	110.289	13.97	676
138.005	120.549	14.48	741
140.775	118.552	18.75	816
135.555	113.19	19.76	874

Experimental Run 2 – Probe A

Wet (g)	Dry (g)	% moisture (gravimetric)	Voltage Output (mv)
97.784	97.65	0.14	92
110.875	110.192	0.62	144
113.211	112.088	1.00	194
111.603	106.43	4.86	278
106.203	102.305	3.81	330

125.656	118.582	5.97	397
127.526	120.397	5.92	421
125.437	114.857	9.21	443
125.306	117.565	6.58	467
126.274	117.277	7.67	489
131.587	122.462	7.45	526
107.993	100.749	7.19	546
133.984	124.396	7.71	550
124.254	114.646	8.38	592
131.001	120.201	8.98	620
135.107	124.504	8.52	653
136.354	122.31	11.48	710
138.809	124.209	11.75	751
141.587	124.51	13.72	798
156.016	131.14	18.97	875

Experimental Run 3 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
95.948	95.827	0.13	94
136.523	135.776	0.55	144
113.665	112.255	1.26	201
113.937	109.223	4.32	282
113.645	109.833	3.47	327
129.657	121.421	6.78	380
124.986	115.858	7.88	398
118.769	110.956	7.04	437
120.665	112.596	7.17	457
117.825	108.873	8.22	485
132.84	122.93	8.06	520
128.7	117.932	9.13	547
123.976	114.365	8.40	564
133.522	121.641	9.77	595
134.911	124.137	8.68	602
136.714	125.209	9.19	629
133.463	123.625	7.96	659
137.648	127.301	8.13	711
151.94	134.238	13.19	764
153.706	131.033	17.30	805

Experimental Run 1 – Probe B

Wet (g)	Dry (g)	% moisture (gravimetric)	Voltage Output (mv)
116.676	116.536	0.12	95
116.396	115.88	0.45	151
110.508	106.582	3.68	182
109.674	103.068	6.41	270
114.013	108.04	5.53	320
107.35	100.576	6.74	374
107.784	102.014	5.66	399
122.876	111.88	9.83	420
103.422	96.299	7.40	462
110.548	99.905	10.65	464
101.085	94.411	7.07	492
115.113	106.609	7.98	502
104.439	96.132	8.64	547
105.208	98.12	7.22	593
100.655	94.304	6.73	613
100.173	91.955	8.94	636
95.098	89.19	6.62	702
138.864	122.472	13.38	763
143.943	123.258	16.78	807
139.217	116.056	19.96	890

Sensor Length 1.5 cm

Experimental Run 1 – Probe A

Wet (g)	Dry (g)	% moisture (gravimetric)	Voltage Output (mv)
34.757	34.682	0.22	33
31.379	30.226	3.81	80
30.33	28.981	4.65	140
30.323	28.745	5.49	173
27.931	26.219	6.53	233
38.047	35.859	6.10	250
31.881	29.981	6.34	274
30.896	29.106	6.15	301
27.012	25.484	6.00	324
30.978	29.1	6.45	364
30.33	28.36	6.95	380

34.366	31.992	7.42	405
28.303	24.582	15.14	427
30.644	26.863	14.08	451
28.246	24.266	16.40	477
35.271	29.778	18.45	518
29.76	25.253	17.85	578
31.867	27.176	17.26	610
38.702	32.143	20.41	680
41.758	33.43	24.91	751

Experimental Run 2 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
34.957	34.902	0.16	37
27.997	27.384	2.24	80
33.068	31.567	4.75	133
29.794	28.055	6.20	181
28.642	27.228	5.19	219
26.887	25.479	5.53	255
35.402	33.5	5.68	275
25.009	23.681	5.61	306
26.583	24.812	7.14	335
29.901	28.102	6.40	345
25.489	23.961	6.38	372
36.896	34.259	7.70	401
33.827	29.386	15.11	442
33.716	29.087	15.91	451
27.141	23.661	14.71	479
30.731	26.414	16.34	532
39.193	32.765	19.62	587
33.608	28.095	19.62	633
49.859	41.074	21.39	669
49.698	40.639	22.29	761

Experimental Run 3 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
39.084	38.952	0.34	47
30.274	29.58	2.35	86

32.832	31.625	3.82	127
34.29	32.831	4.44	179
32.28	30.726	5.06	226
34.802	32.82	6.04	254
35.566	33.626	5.77	283
32.307	30.099	7.34	312
30.025	28.351	5.90	350
32.264	30.007	7.52	372
28.982	27.101	6.94	406
38.004	35.022	8.51	436
31.833	29.449	8.10	458
42.646	37.706	13.10	482
36.865	33.486	10.09	538
38.145	32.219	18.39	580
38.975	32.787	18.87	640
39.931	32.843	21.58	692
51.175	41.53	23.22	750

Experimental Run 1 – Probe B

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
31.791	31.701	0.28	38
30.79	29.584	4.08	74
32.202	30.652	5.06	141
32.129	30.568	5.11	185
33.718	31.942	5.56	221
30.949	29.281	5.70	262
34.888	32.479	7.42	286
26.533	24.418	8.66	309
25.666	23.656	8.50	335
42.062	38.141	10.28	351
34.485	29.742	15.95	388
27.704	24.578	12.72	398
25.424	21.95	15.83	428
24.933	21.552	15.69	451
31.736	27.456	15.59	475
29.549	25.132	17.58	537
27.25	23.141	17.76	577
32.615	27.436	18.88	636
31.999	26.165	22.30	684
49.895	40.364	23.61	753

Sensor Length 1.0 cm

Experimental Run 1 – Probe A

Wet (g)	Dry (g)	% moisture (gravimetric)	Voltage Output (mv)
26.363	26.265	0.37	20
21.124	20.514	2.97	65
16.621	15.981	4.00	96
23.87	22.651	5.38	141
16.302	14.922	9.25	184
20.824	18.47	12.74	243
20.73	18.402	12.65	268
26.934	24.399	10.39	284
26.505	22.705	16.74	302
20.603	18.163	13.43	320
23.909	20.157	18.61	341
24.841	20.58	20.70	357
21.935	18.624	17.78	382
21.997	18.479	19.04	404
22.812	19.3	18.20	415
27.961	22.838	22.43	464
26.484	21.575	22.75	505
22.527	18.413	22.34	539
25.713	20.633	24.62	622
27.694	22.767	21.64	655

Experimental Run 2 – Probe A

Wet (g)	Dry (g)	% moisture (gravimetric)	Voltage Output (mv)
20.193	19.972	1.11	38
20.992	20.616	1.82	56
26.208	24.407	7.38	117
22.29	21.011	6.09	158
22.178	20.062	10.55	201
21.165	18.591	13.85	223
16.449	15.024	9.48	252
18.206	16.376	11.17	281
22.359	19.692	13.54	295
23.56	20.615	14.29	329
22.956	20.125	14.07	340
26.182	23.339	12.18	380

30.741	25.876	18.80	408
32.546	27.377	18.88	425
25.356	21.389	18.55	455
25.303	21.496	17.71	504
22.607	19.118	18.25	546
39.065	31.537	23.87	589
33.959	28.369	19.70	595
30.597	25.111	21.85	636

Experimental Run 3 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
22.485	22.43	0.25	20
21.211	20.973	1.13	65
24.262	23.532	3.10	119
22.04	21.156	4.18	153
29.573	28.226	4.77	199
17.735	16.692	6.25	230
17.344	16.29	6.47	244
26.173	24.539	6.66	279
17.336	16.198	7.03	294
20.226	18.789	7.65	328
17.798	16.2	9.86	358
19.873	18.162	9.42	381
17.763	16.199	9.65	409
21.971	19.866	10.60	433
20.437	18.17	12.48	456
19.611	17.356	12.99	507
22.225	19.466	14.17	537
21.37	18.042	18.45	573
23.256	19.948	16.58	633
29.387	23.773	23.62	673

Experimental Run 1 – Probe B

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
31.827	31.35	1.52	26
17.994	17.611	2.17	55
12.692	12.238	3.71	146
16.195	15.018	7.84	180

18.4	16.711	10.11	224
20.671	18.649	10.84	236
22.077	19.667	12.25	259
22.561	19.679	14.65	280
16.479	14.843	11.02	300
17.728	15.221	16.47	317
23.705	20.072	18.10	339
21.985	18.848	16.64	365
18.856	15.811	19.26	376
23.641	20.002	18.19	397
31.101	25.552	21.72	425
24.693	20.607	19.83	454
22.898	18.642	22.83	508
25.791	21.332	20.90	536
25.789	20.832	23.80	573
23.719	19.188	23.61	619

Sensor Length 0.5 cm

Experimental Run 1 – Probe A

Wet (g)	Dry (g)	% moisture (gravimetric)	Voltage Output (mv)
17.36	17.345	0.09	22
11.502	11.286	1.91	50
10.124	9.641	5.01	97
8.591	8.21	4.64	132
9.344	8.513	9.76	176
8.102	7.436	8.96	201
10.978	9.704	13.13	230
11.973	10.449	14.59	250
8.684	7.756	11.96	273
11.372	9.852	15.43	301
11.845	10.332	14.64	321
14.617	11.891	22.92	383
15.717	13.114	19.85	407
17.026	13.772	23.63	425
19.41	15.795	22.89	464
21.962	18.319	19.89	506
16.658	13.496	23.43	541
18.586	14.971	24.15	595
21.505	17.318	24.18	624

Experimental Run 2 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
23.087	23.05	0.16	24
16.59	16.203	2.39	56
14.226	13.335	6.68	105
17.218	16.171	6.47	137
11.991	10.946	9.55	187
11.796	10.999	7.25	194
15.875	14.507	9.43	216
15.233	13.955	9.16	247
12.25	10.645	15.08	284
18.458	15.97	15.58	298
17.367	14.966	16.04	329
13.539	11.286	19.96	359
14.276	11.926	19.70	380
16.642	13.999	18.88	401
14.611	12.066	21.09	422
16.521	13.408	23.22	458
14.657	11.901	23.16	498
15.929	12.835	24.11	545
13.962	11.329	23.24	578
16.287	13.167	23.70	623

Experimental Run 3 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
13.525	13.005	4.0	65
12.249	11.544	6.1	18
14.278	13.416	6.4	94
12.956	11.918	8.7	125
12.37	11.003	12.4	240
20.865	17.962	16.2	353
13.13	11.248	16.7	226
13.694	11.578	18.3	154
12.415	10.431	19.0	168
14.102	11.724	20.3	424
14.033	11.511	21.9	296
12.158	9.906	22.7	271
14.316	11.628	23.1	503

13.354	10.814	23.5	337
13.762	11.122	23.7	583
15.093	12.156	24.2	405
17.448	14.004	24.6	553
15.656	12.556	24.7	382
17.76	14.229	24.8	467
16.773	13.342	25.7	630

Experimental Run 1 – Probe B

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
22.48	22.407	0.33	21
14.708	14.207	3.53	58
14.795	14.204	4.16	98
9.794	9.158	6.94	130
10.567	9.727	8.64	171
11.554	10.561	9.40	197
12.75	11.573	10.17	230
14.73	13.375	10.13	256
11.935	10.441	14.31	270
11.272	9.886	14.02	290
12.893	11.053	16.65	333
11.355	9.789	16.00	343
12.018	10.348	16.14	383
14.662	12.536	16.96	407
14.624	12.452	17.44	430
19.323	15.934	21.27	475
17.077	13.942	22.49	492
13.251	10.856	22.06	557
14.825	12.1	22.52	576
16.5	13.339	23.70	630

Kill Devil Hills, North Carolina

Sensor Length 6.0 cm

Experimental Run 1 – Probe A

Wet (g)	Dry (g)	% Moisture (gravimetric)	Voltage Output (mv)
117.956	114.97	2.60	125
103.842	100.913	2.90	205
106.003	102.819	3.10	143
118.472	114.515	3.46	169
114.724	110.574	3.75	300
112.239	107.53	4.38	284
112.658	107.346	4.95	371
99.785	94.88	5.17	400
113.437	106.624	6.39	440
119.367	111.219	7.33	489
119.848	110.423	8.54	535
111.183	102.332	8.65	595
116.371	104.255	11.62	634
118.252	105.757	11.81	771
129.968	116.172	11.88	685
132.305	117.175	12.91	706
97.602	84.651	15.30	835
122.363	105.711	15.75	903
124.895	107.896	15.75	885
149.785	125.911	18.96	938

Experimental Run 2 – Probe A

Wet (g)	Dry (g)	% Moisture (gravimetric)	Voltage Output (mv)
101.1	100.188	0.91	138
99.183	97.063	2.18	145
106.863	103.4	3.35	281
110.674	106.812	3.62	310
116.357	112.091	3.81	193
110.301	105.513	4.54	370
110.398	105.446	4.70	237
84.028	79.713	5.41	410
106.804	100.658	6.11	438
105.374	97.866	7.67	545

109.237	100.588	8.60	505
128.714	117.891	9.18	576
119.986	108.75	10.33	632
118.421	105.806	11.92	685
111.286	99.173	12.21	734
115.513	101.736	13.54	798
114.171	100.404	13.71	769
142.809	124.773	14.46	940
124.162	105.825	17.33	893
118.419	100.569	17.75	847

Experimental Run 3 – Probe A

Wet (g)	**Dry (g)**	**% Moisture (gravimetric)**	**Voltage Output (mv)**
101.595	99.463	2.14	112
105.218	102.967	2.19	143
103.313	100.035	3.28	226
99.978	96.79	3.29	311
119.392	115.03	3.79	176
108.651	104.454	4.02	274
103.309	99.189	4.15	354
105.958	101.687	4.20	397
114.837	108.797	5.55	459
103.663	96.724	7.17	495
103.619	96.611	7.25	596
97.215	89.971	8.05	547
114.896	104.348	10.11	615
108.668	97.762	11.16	672
110.235	98.99	11.36	716
111.88	99.493	12.45	777
113.813	100.369	13.39	818
128.147	110.138	16.35	848
139.66	119.044	17.32	909
125.542	105.488	19.01	941

Experimental Run 1 – Probe B

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
109.13	107.876	1.16	118
106.244	103.823	2.33	143

111.616	108.921	2.47	180
106.037	103.151	2.80	212
93.794	90.11	4.09	444
115.927	111.313	4.15	265
100.351	96.342	4.16	353
105.388	100.85	4.50	304
107.379	102.467	4.79	406
117.95	109.713	7.51	511
116.443	107.614	8.20	620
117.619	108.619	8.29	595
120.076	110.064	9.10	534
112.659	102.41	10.01	688
113.968	101.176	12.64	733
119.883	105.064	14.10	803
124.361	108.706	14.40	779
124.715	107.111	16.44	864
133.939	113.695	17.81	907
140.859	118.511	18.86	918

Sensor Length 1.5 cm

Experimental Run 1 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
26.151	26.12	0.12	29
30.423	29.949	1.58	59
22.843	22.028	3.70	97
42.735	40.549	5.39	167
31.521	29.858	5.57	139
40.222	37.543	7.14	208
40.112	36.383	10.25	355
35.783	32.327	10.69	230
41.669	37.163	12.12	377
37.813	33.652	12.36	283
41.333	36.726	12.54	420
42.367	37.346	13.44	451
41.325	35.997	14.80	304
41.532	35.874	15.77	490
42.957	36.581	17.43	584
47	39.232	19.80	692
39.214	32.7	19.92	623
50.772	41.76	21.58	663

Experimental Run 2 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
31.277	31.193	0.27	39
28.202	27.781	1.52	67
26.276	25.584	2.70	101
30.707	29.523	4.01	142
29.339	27.939	5.01	165
33.846	31.762	6.56	203
32.561	29.628	9.90	348
44.49	40.376	10.19	377
40.963	36.924	10.94	277
32.778	29.198	12.26	243
34.288	30.314	13.11	442
33.922	29.464	15.13	303
34.921	30.176	15.72	412
37.495	32.247	16.27	526
49.018	41.819	17.21	657
40.67	34.48	17.95	630
41.631	35.215	18.22	693
38.946	32.938	18.24	486
35.824	30.185	18.68	599
40.074	33.646	19.10	559

Experimental Run 3 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
31.894	31.705	0.60	38
27.85	27.295	2.03	57
32.177	31.214	3.09	100
35.623	33.863	5.20	139
31.346	29.546	6.09	205
36.969	34.677	6.61	181
28.925	26.258	10.16	281
28.863	26.089	10.63	249
33.323	30.067	10.83	320
32.967	29.102	13.28	338
26.364	23.1359	13.95	417
31.342	27.452	14.17	385
37.496	32.168	16.56	483

34.988	29.999	16.63	627
37.007	31.717	16.68	446
39.32	33.566	17.14	516
38.979	32.738	19.06	550
39.648	33.168	19.54	595
40.646	33.34	21.91	672
38.85	31.838	22.02	712

Experimental Run 1 – Probe B

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
34.318	34.124	0.57	38
34.173	33.131	3.15	104
31.955	30.875	3.50	59
33.677	32.052	5.07	179
28.127	26.66	5.50	137
31.776	29.033	9.45	276
31.259	28.507	9.65	240
29.916	27.133	10.26	201
29.747	26.81	10.95	314
27.629	24.68	11.95	342
30.373	26.824	13.23	419
33.012	28.708	14.99	376
33.644	29.11	15.58	649
24.852	21.388	16.20	485
37.803	32.172	17.50	445
38.689	32.441	19.26	552
33.6	28.087	19.63	527
34.2999	28.17	21.76	596
40.266	33.004	22.00	623
51.718	42.309	22.24	704

Sensor Length 1.0 cm

Experimental Run 1 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
30.293	30.004	0.96	25

33.545	31.991	4.86	47
24.707	23.738	4.08	74
24.747	23.665	4.57	130
25.635	24.099	6.37	144
22.132	19.976	10.79	187
24.608	21.69	13.45	221
28.9	25.013	15.54	255
30.825	26.686	15.51	298
30.633	26.669	14.86	331
27.555	23.409	17.71	367
27.78	23.541	18.01	409
34.428	29.362	17.25	422
33.897	28.242	20.02	467
31.723	27.171	16.75	506
34.414	28.989	18.71	547
32.321	27.096	19.28	571
34.954	28.845	21.18	620
30.558	24.782	23.31	663
33.687	27.569	22.19	690

Experimental Run 2 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
18.241	18.194	0.26	25
20.392	19.885	2.55	41
23.428	22.419	4.50	75
18.197	17.689	2.87	125
16.511	15.476	6.69	165
32.326	29.065	11.22	200
29.535	25.964	13.75	225
31.531	26.554	18.74	267
38.33	32.751	17.03	302
34.004	29.59	14.92	328
30.253	26.331	14.89	368
28.554	24.259	17.70	414
34.36	29.017	18.41	428
29.411	24.158	21.74	471
29.975	25.052	19.65	511
28.804	24.51	17.52	532
36.669	30.134	21.69	577
33.7	27.839	21.05	602
42.058	34.543	21.76	627
36.635	29.897	22.54	644

Experimental Run 3 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
20.97	20.628	1.66	53
23.415	23.277	0.59	89
25.21	24.703	2.05	113
20.865	19.926	4.71	147
26.07	24.112	8.12	199
25.358	23.539	7.73	221
28.825	26.595	8.39	250
27.503	24.105	14.10	303
28.61	24.671	15.97	329
31.529	28.471	10.74	366
29.821	26.251	13.60	402
26.708	22.575	18.31	434
27.535	23.965	14.90	470
28.841	24.725	16.65	505
30.313	25.085	20.84	546
29.585	24.396	21.27	579
24.713	24.683	23.62	604
30.513	24.683	23.62	649
28.48	23.178	22.88	660

Experimental Run 1 – Probe B

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
24.654	24.616	0.15	23
29.442	28.991	1.56	51
22.278	21.712	2.61	84
23.387	22.259	5.07	121
24.45	23.058	6.04	145
21.267	20.228	5.14	182
21.146	18.703	13.06	221
22.885	20.492	11.68	262
29.412	25.047	17.43	298
28.36	23.688	19.72	335
33.805	28.686	17.84	367
34.142	28.956	17.91	411
25.6	21.671	18.13	437
26.567	22.685	17.11	470
25.549	21.518	18.73	515

30.27	25.027	20.95	577
28.635	23.676	20.95	610
31.668	25.96	21.99	628
33.969	27.885	21.82	636

Sensor Length 1.0 cm

Experimental Run 1 – Probe A

Wet (g)	Dry (g)	% moisture (gravimetric)	Voltage Output (mv)
14.047	13.943	0.75	30
12.86	12.55	2.47	56
13.339	12.273	8.69	97
12.591	11.482	9.66	120
16.165	13.956	15.83	155
17.653	14.728	19.86	203
14.991	12.445	20.46	177
16.705	13.855	20.57	252
14.133	11.684	20.96	401
14.713	12.143	21.16	276
11.368	9.256	22.82	346
13.676	11.091	23.31	227
17.206	13.925	23.56	304
16.131	13.046	23.65	451
18.609	15.004	24.03	425
17.504	14.103	24.12	471
21.71	17.491	24.12	537
18.528	14.903	24.32	505

Experimental Run 2 – Probe A

Wet (g)	Dry (g)	% moisture (gravimetric)	Voltage Output (mv)
12.152	12.033	0.99	29
12.609	12.309	2.44	53
13.316	12.729	4.61	80
9.309	8.466	9.96	102
11.063	9.828	12.57	125
9.264	7.898	17.30	196

15.391	12.95	18.85	176
13.753	11.442	20.20	227
12.229	10.072	21.42	378
14.673	12.049	21.78	271
13.292	10.86	22.39	356
14.443	11.787	22.53	302
18.044	14.709	22.67	471
12.627	10.28	22.83	446
15.756	12.797	23.12	246
14.739	11.951	23.33	323
15.029	12.186	23.33	420
24.136	19.536	23.55	408
28.661	23.172	23.69	545

Experimental Run 3 – Probe A

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
18.062	18.042	0.11	26
10.526	10.365	1.55	51
8.169	7.899	3.42	97
15.625	15.071	3.68	75
13.811	11.703	18.01	126
12.054	10.156	18.69	197
13.98	11.754	18.94	178
19.125	16.07	19.01	225
14.342	11.914	20.38	295
13.185	10.915	20.80	153
12.806	10.601	20.80	324
11.085	9.169	20.90	255
13.82	11.376	21.48	276
20.565	16.703	23.12	430
14.895	12.037	23.74	403
17.262	13.941	23.82	477
15.563	12.525	24.26	392
12.681	10.198	24.35	450
24.205	19.427	24.59	544

Experimental Run 1 – Probe B

Wet (g)	**Dry (g)**	**% moisture (gravimetric)**	**Voltage Output (mv)**
14.047	13.943	0.75	30
12.86	12.55	2.47	56
13.339	12.273	8.69	97
12.591	11.482	9.66	120
16.165	13.956	15.83	155
17.653	14.728	19.86	203
14.991	12.445	20.46	177
16.705	13.855	20.57	252
14.133	11.684	20.96	401
14.713	12.143	21.16	276
11.368	9.256	22.82	346
13.676	11.091	23.31	227
17.206	13.925	23.56	304
16.131	13.046	23.65	451
18.609	15.004	24.03	425
17.504	14.103	24.12	471
21.71	17.491	24.12	537
18.528	14.903	24.32	505

Vita

Phillip Schmutz was born in Metairie, Louisiana in 1981. He grew up in Lake Charles, Louisiana until he moved to Tyler, Texas during high school. After graduating in 2000 from Robert E. Lee High School, he went to Baylor University where he earned a Bachelor of Arts in Geography and Environmental Studies. During his time at Baylor he developed a profound interest in the physical processes of the coastal environment, thanks in part to Dr. Jennifer Rahn. Through her guidance and support Phillip found himself embarking on the next chapter of his life at Louisiana State University. Upon completion of his master's degree from LSU, he will continue his education in geography and pursue a doctoral degree from the same institution.