Nondestructive measurement system to determine corn seed planting depth using ground penetrating radar for precision agriculture

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Nondestructive measurement system to determine corn seed planting depth using ground penetrating radar for precision agriculture

by

Kenneth Obrien Mpho Mapoka

A dissertation submitted to the graduate faculty
in partial fulfillment of the requirements for the degree of

DOCTOR OF PHILOSOPHY

Major: Agricultural and Biosystems Engineering

Program of Study Committee:
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The student author, whose presentation of the scholarship herein was approved by the program of study committee, is solely responsible for the content of this dissertation. The Graduate College will ensure this dissertation is globally accessible and will not permit alterations after a degree is conferred.

Iowa State University
Ames, Iowa
2018

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DEDICATION

To my grandmother, mother, sisters, and fiancée. Thank you for all your support and encouragement.

And

To the loving memory of my grandfather, Elias Matumo Mapoka.
# TABLE OF CONTENTS

<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>LIST OF TABLES</td>
<td>vii</td>
</tr>
<tr>
<td>LIST OF FIGURES</td>
<td>x</td>
</tr>
<tr>
<td>ACKNOWLEDGEMENTS</td>
<td>xvii</td>
</tr>
<tr>
<td>ABSTRACT</td>
<td>xviii</td>
</tr>
<tr>
<td>CHAPTER 1. GENERAL INTRODUCTION</td>
<td>1</td>
</tr>
<tr>
<td>1.1 Introduction</td>
<td>1</td>
</tr>
<tr>
<td>1.1.1 Planting depth control</td>
<td>3</td>
</tr>
<tr>
<td>1.1.2 Planting depth Variability</td>
<td>3</td>
</tr>
<tr>
<td>1.1.3 Motivation</td>
<td>4</td>
</tr>
<tr>
<td>1.2 Research Objectives</td>
<td>6</td>
</tr>
<tr>
<td>1.2.1 Specific objectives</td>
<td>6</td>
</tr>
<tr>
<td>1.2.2 GPR background</td>
<td>6</td>
</tr>
<tr>
<td>1.2.3 GPR theory and constitutive properties</td>
<td>8</td>
</tr>
<tr>
<td>1.2.4 Dielectric materials, properties, and polarization</td>
<td>10</td>
</tr>
<tr>
<td>1.2.5 GPR data acquisition modes and wave propagation</td>
<td>13</td>
</tr>
<tr>
<td>1.2.6 GPR data visualization and processing</td>
<td>16</td>
</tr>
<tr>
<td>1.2.7 GPR wave velocity correction</td>
<td>19</td>
</tr>
<tr>
<td>1.3 Dissertation Organization</td>
<td>20</td>
</tr>
<tr>
<td>1.4 Publications or Submitted Manuscripts</td>
<td>21</td>
</tr>
<tr>
<td>1.4.1 Submitted papers</td>
<td>21</td>
</tr>
<tr>
<td>1.4.2 Referenced conference articles</td>
<td>22</td>
</tr>
<tr>
<td>References</td>
<td>22</td>
</tr>
<tr>
<td>CHAPTER 2. A COMPREHENSIVE SURVEY OF NONDESTRUCTIVE SENSING TECHNOLOGIES FOR THE DETECTION OF CORN SEEDS IN A CLOSED TRENCH AND MEASURING PLANTING DEPTH TO AUGMENT THE CONVENTIONAL METHOD</td>
<td>26</td>
</tr>
</tbody>
</table>
## Abstract

2.1 Introduction ........................................ 27

2.2 Measuring Corn Seed Planting Depth Strategies ................................. 29
  2.2.1 Planter kinematics ................................ 29
  2.2.2 Soil subsurface detection ............................. 30

2.3 Sensing Technology Classification ........................................ 42
  2.3.1 Subsurface detection ................................ 42
  2.3.2 Suitability of technologies to detect and range corn seeds ...... 42

2.4 Nondestructive Sensor Application For SD-KI for Agricultural Development ... 47

2.5 Conclusion ........................................ 48

References ........................................ 49

### CHAPTER 3. USING GPRMAX TO MODEL A GROUND PENETRATING RADAR (GPR) TO LOCATE AGRICULTURAL CORN SEED AS AN ATTEMPT TO MEASURE PLANTING DEPTH

Abstract ........................................ 57

3.1 Introduction ........................................ 58
  3.1.1 Soil mixing model ................................ 59
  3.1.2 GPR operation principles ............................. 60
  3.1.3 Electromagnetic theory ................................ 60
  3.1.4 gprMax modeling .................................. 61

3.2 Methodology ........................................ 63
  3.2.1 Seed model properties ................................ 63
  3.2.2 Soil model properties ................................ 65
  3.2.3 Model of a seed in the soil ........................... 67

3.3 Simulation Results and Discussion ........................................ 69
  3.3.1 Soil bulk density and frequency ....................... 72

3.4 Simulation Model Verification ........................................ 76

3.5 Experimental Verification ........................................ 78
  3.5.1 Experimental results and discussion .................. 79

3.6 Conclusion ........................................ 81

References ........................................ 83

### CHAPTER 4. EXPERIMENTAL APPROACH TO QUANTIFYING CORN SEED SIMULANT MEASUREMENT ERROR USING A GROUND PENETRATING RADAR

References ........................................ 87
<table>
<thead>
<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Abstract</td>
<td>87</td>
</tr>
<tr>
<td>4.1 Introduction</td>
<td>88</td>
</tr>
<tr>
<td>4.2 Material and Procedures</td>
<td>90</td>
</tr>
<tr>
<td>4.2.1 Synthetic corn seeds (SCS)</td>
<td>90</td>
</tr>
<tr>
<td>4.2.2 Soils</td>
<td>91</td>
</tr>
<tr>
<td>4.2.3 Soil bins experimental setup</td>
<td>92</td>
</tr>
<tr>
<td>4.2.4 Data collection, Processing and Identification of SCS</td>
<td>94</td>
</tr>
<tr>
<td>4.2.5 Amplitude normalization</td>
<td>96</td>
</tr>
<tr>
<td>4.2.6 Estimation of Two-Way Travel Time (TWTT)</td>
<td>97</td>
</tr>
<tr>
<td>4.2.7 Estimation planting depth (PD)</td>
<td>98</td>
</tr>
<tr>
<td>4.2.8 GPR measurement error (ME)</td>
<td>100</td>
</tr>
<tr>
<td>4.2.9 Data analysis</td>
<td>100</td>
</tr>
<tr>
<td>4.3 Results</td>
<td>101</td>
</tr>
<tr>
<td>4.3.1 1.6 GHz antenna</td>
<td>101</td>
</tr>
<tr>
<td>4.3.2 2.6 GHz antenna</td>
<td>104</td>
</tr>
<tr>
<td>4.4 Statistical Analysis</td>
<td>110</td>
</tr>
<tr>
<td>4.4.1 The 1.6 GHz antenna</td>
<td>110</td>
</tr>
<tr>
<td>4.4.2 The 2.6 GHz antenna</td>
<td>111</td>
</tr>
<tr>
<td>4.4.3 Discussion</td>
<td>113</td>
</tr>
<tr>
<td>4.5 Conclusion</td>
<td>115</td>
</tr>
<tr>
<td>References</td>
<td>116</td>
</tr>
</tbody>
</table>

CHAPTER 5. APPLICATION OF GROUND-PENETRATING RADAR IN
MEASURING CORN SEED SPACING AND PLANTING DEPTHS IN
DIFFERENT SOILS                                           117

Abstract                                                117
5.1 Introduction                                        118
5.2 Materials and Methods                               120
5.2.1 Soils                                             120
5.2.2 Field-corn seeds                                 121
5.2.3 Ground Penetrating Radar (GPR)                    122
5.2.4 Data collection                                  123
5.2.5 Application of image processing for discrimination of CS responses  125
5.2.6 Corn seed depth                                  126
5.2.7 Data analysis methods                            128
5.3 Results                                             128
<table>
<thead>
<tr>
<th>Section</th>
<th>Title</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.3.1</td>
<td>GPR image processing using Fast Discrete Curvelet Transform</td>
<td>131</td>
</tr>
<tr>
<td>5.3.2</td>
<td>Statistical analysis</td>
<td>134</td>
</tr>
<tr>
<td>5.3.3</td>
<td>Discussion</td>
<td>136</td>
</tr>
<tr>
<td>5.4</td>
<td>Conclusion</td>
<td>139</td>
</tr>
<tr>
<td>References</td>
<td></td>
<td>139</td>
</tr>
</tbody>
</table>

**CHAPTER 6. MANUAL AND GROUND PENETRATING RADAR FIELD MEASUREMENTS OF FIELD-CORN SPACING, PLANTING DEPTH, AND FURROW FEATURE IDENTIFICATION**

Abstract | 141
6.1 Introduction | 142
6.2 Materials and Methods | 142
  6.2.1 Farm site description | 142
  6.2.2 GPR Data collection | 145
  6.2.3 Data processing | 147
  6.2.4 Feature extraction and furrow identification process | 148
6.3 Data Analysis | 149
6.4 Results and Discussion | 149
  6.4.1 Manual measurements | 149
  6.4.2 GPR measurements | 153
6.5 Conclusion | 163
  6.5.1 Future work | 164
References | 165

**CHAPTER 7. GENERAL CONCLUSION**

7.1 Conclusion | 166
7.2 Recommendations for Future work | 168

**APPENDIX A. DIELECTRIC PERMITTIVITY MODELS** | 170

**APPENDIX B. FEW ADDITIONAL PLANTING DEPTH DATA POINTS DETERMINED USING THE MATCH-UP AND SELECTION ALGORITHM** | 171
### LIST OF TABLES

<table>
<thead>
<tr>
<th>Table</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Table 2.1</td>
<td>Classification of sensor based on their sensing type, operating frequency, operation, cost, process, and safety</td>
<td>54</td>
</tr>
<tr>
<td>Table 2.2</td>
<td>Suitability and Comparative study of requirements for detection of Seeds</td>
<td>55</td>
</tr>
<tr>
<td>Table 2.3</td>
<td>Specific applications for each non-destructive technique discussed in this review</td>
<td>56</td>
</tr>
<tr>
<td>Table 3.1</td>
<td>Soil Composition values to Determine Soil Dielectric Properties</td>
<td>66</td>
</tr>
<tr>
<td>Table 3.2</td>
<td>Estimating soil dielectric permittivity and soil electrical conductivity simulation parameters of sandy loam, loam, and clay at different soil bulk densities and five soil VMC</td>
<td>67</td>
</tr>
<tr>
<td>Table 3.3</td>
<td>Dielectric permittivity and soil electrical conductivity simulation parameters of sandy loam, loam, and clay estimated at five VMC and soil bulk density greater than maximum possible density</td>
<td>67</td>
</tr>
<tr>
<td>Table 3.4</td>
<td>Simulation obtained from different VMC, and a soil bulk density of 1.42 g cm(^{-3}) in sandy loam soil using an antenna frequency of 1.6 GHz</td>
<td>72</td>
</tr>
<tr>
<td>Table 3.5</td>
<td>Simulation obtained from different VMC, and a soil bulk density of 1.2 g cm(^{-3}) in loam soil using an antenna frequency of 1.6 GHz</td>
<td>73</td>
</tr>
<tr>
<td>Table 3.6</td>
<td>The effect of simulation frequency on obtaining a response amplitude from natural corn seed model at different soil VMC, and a soil bulk density of 1.42 g cm(^{-3}) in sandy loam soil using an antenna frequency of 2.6 GHz</td>
<td>73</td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>-------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>3.7</td>
<td>Experimental results obtained from different VMC, and a soil bulk density of (1.41 \text{ g cm}^{-3}) in sandy loam soil using an antenna frequency of (2.6 \text{ GHz}) and field corn variety: P0339AMXT PDR size. .......... 81</td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>Comparison summary of real corn and synthetic corn seed properties 91</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>Soil characterization summary ................................. 92</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>Detection rate in non-saline sandy loam and loam soils with metal and wood seeds ................................................................. 107</td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>Detection rate in saline sandy loam and loam soils with metal and wood seeds ................................................................. 107</td>
<td></td>
</tr>
<tr>
<td>4.5</td>
<td>Topp’s dielectric model parameter estimation for all the SMS (1.6 GHz antenna) ................................................................. 111</td>
<td></td>
</tr>
<tr>
<td>4.6</td>
<td>Soil mixing method parameter estimation for SMS ME (2.6 GHz antenna) ................................................................. 112</td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td>Topp’s dielectric method parameter estimation for SWS ME (2.6 GHz antenna) ................................................................. 112</td>
<td></td>
</tr>
<tr>
<td>5.1</td>
<td>Soil information used in the study. ........................................ 120</td>
<td></td>
</tr>
<tr>
<td>5.2</td>
<td>Configured system control parameters for the SIR-3000 unit .... 124</td>
<td></td>
</tr>
<tr>
<td>5.3</td>
<td>Classification of soil VMC groups ..................................... 124</td>
<td></td>
</tr>
<tr>
<td>5.4</td>
<td>Descriptive statistics comparison of GPR estimated CS depth in dry sandy-loam and loam soils according to the CS spacing .......... 135</td>
<td></td>
</tr>
<tr>
<td>5.5</td>
<td>The percentage of seeds detected within the CP3 value from the 2.6 GHz antenna per soil VMC group ........................................ 135</td>
<td></td>
</tr>
<tr>
<td>5.6</td>
<td>Analysis of variance on the effect of each treatment factor in the prediction of CS planting depth error based on the three dielectric models. ........................................ 136</td>
<td></td>
</tr>
<tr>
<td>Table</td>
<td>Description</td>
<td>Page</td>
</tr>
<tr>
<td>---------</td>
<td>---------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------</td>
<td>------</td>
</tr>
<tr>
<td>5.7</td>
<td>Least Square Means with standard error for the CPDA parameter for all combination of the treatment factors: soil, VMC group and the interaction of the soils and VMC groups</td>
<td>136</td>
</tr>
<tr>
<td>6.1</td>
<td>Field soil information used in the study</td>
<td>143</td>
</tr>
<tr>
<td>6.2</td>
<td>Averaged corn seed planting depth measurement with corresponding standard deviations according to seed spacing, and selected row-unit downforce.</td>
<td>150</td>
</tr>
<tr>
<td>6.3</td>
<td>ANOVA of the downforces.</td>
<td>151</td>
</tr>
<tr>
<td>6.4</td>
<td>Tukey multiple comparisons of means at 5% level of confidence.</td>
<td>151</td>
</tr>
<tr>
<td>6.5</td>
<td>The percentage of seedlings emergence within the CP3 value</td>
<td>151</td>
</tr>
<tr>
<td>A.1</td>
<td>Dielectric permittivity models</td>
<td>170</td>
</tr>
<tr>
<td>B.1</td>
<td>Two-way travel time (TWTT) and dielectric permittivity sample data used to estimate corn seed planting depths in sandy-loam and loam soils at different moisture contents.</td>
<td>171</td>
</tr>
</tbody>
</table>
# LIST OF FIGURES

<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>Figure 1.1</td>
<td>Conventional method of quantifying sown seed planting depth (ISO, 2018)</td>
<td>5</td>
</tr>
<tr>
<td>Figure 1.2</td>
<td>Effects of increasing soil water and clay contents on electrical conductivity</td>
<td>12</td>
</tr>
<tr>
<td>Figure 1.3</td>
<td>Presents cut-off frequency response and relaxation effect for different polarization mechanisms</td>
<td>13</td>
</tr>
<tr>
<td>Figure 1.4</td>
<td>Shielded Transmitter and Receiver antenna from external signal interference. TX and RX represent a measured signal</td>
<td>15</td>
</tr>
<tr>
<td>Figure 1.5</td>
<td>Wave directionality of the (a) unshielded and (b) shielded antenna</td>
<td>15</td>
</tr>
<tr>
<td>Figure 1.6</td>
<td>Propagation and Reflection of layered earth model; equal reflectivity horizons, low and high attenuation</td>
<td>16</td>
</tr>
<tr>
<td>Figure 1.7</td>
<td>Time-dependent gain function manipulation to enhance the deep attenuated waves in the subsurface (a) Low resolution GPR A-scan before gain correction, (b) time-varying gains that compensate for weak amplitudes to improve resolution, and (c) High resolution GPR A-scan before gain correction.</td>
<td>16</td>
</tr>
<tr>
<td>Figure 1.8</td>
<td>B scan</td>
<td>17</td>
</tr>
<tr>
<td>Figure 1.9</td>
<td>Summary of GPR image processing flow.</td>
<td>19</td>
</tr>
<tr>
<td>Figure 2.1</td>
<td>Classification of sensing technologies for possible detection of corn seeds in a closed trench</td>
<td>29</td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>Figure 2.2</td>
<td>The principle of operation for a nondestructive sensor for plant depth detection in a closed trench. <em>Where, $T_x$ is the antenna transmitter, $R_x$ is the antenna receiver $\rho_i$ is the material density, $T_i$ is the material temperature, $\epsilon_i$ is the dielectric constant, $\mu_i$ is the magnetic permeability, $\sigma_i$ is the electrical conductivity.</em> 31</td>
<td></td>
</tr>
<tr>
<td>Figure 2.3</td>
<td>Electromagnetic Wave Spectrum (Rossel et al., 2011) 37</td>
<td></td>
</tr>
<tr>
<td>Figure 3.1</td>
<td>GPR operational principles showing antenna separation, air, transmitted, refracted, reflected waves from air-soil and soil-seed interfaces 61</td>
<td></td>
</tr>
<tr>
<td>Figure 3.2</td>
<td>(a) Images of corn shapes, including: circular/roundish/sphere shapes (i, ii, vi), and triangular/conical shapes (iii, iv, v) and measurement of the corn physical parameter using a digital caliper 64</td>
<td></td>
</tr>
<tr>
<td>Figure 3.3</td>
<td>(a) A 2D model of an embedded seed 0.07 m deep in the soil with pulsing antenna source placed directly on top of the soil surface. A small section was extracted and enlarged to show cell size and dielectric properties that define each cell, (b) GprMax geometrical model of an embedded spherical seed 0.07 m in a soil media. 68</td>
<td></td>
</tr>
<tr>
<td>Figure 3.4</td>
<td>A-scans to evaluate GPR waves through sandy-loam soil at different volumetric moisture content (VMC) with natural corn seed model of (a) small radius 0.006 m, and (b) large radius of 0.024 m 71</td>
<td></td>
</tr>
<tr>
<td>Figure 3.5</td>
<td>Natural corn seed model response of radius 0.006 m in sandy loam at 15% VMC and soil bulk density (BD) of 1.42 g cm$^{-3}$ (a) B-scan at a center frequency of 1.6 GHz, and (b) B-scan at a center frequency of 2.6 GHz 74</td>
<td></td>
</tr>
<tr>
<td>Figure 3.6</td>
<td>Natural corn seed model response of radius 0.024 m in sandy loam at 15% VMC and soil BD of 1.42 g cm$^{-3}$ (a) B-scan at a center frequency of 1.6 GHz, and (b) B-scan at a center frequency of 2.6 GHz 75</td>
<td></td>
</tr>
<tr>
<td>Figure</td>
<td>Description</td>
<td></td>
</tr>
<tr>
<td>--------</td>
<td>-------------</td>
<td></td>
</tr>
<tr>
<td>3.7</td>
<td>Synthetic metal corn seed of radius 0.006 m on sandy loam at 15% VMC and soil BD of 1.42 g cm(^{-3}) (a) B-scan at a center frequency of 1.6 GHz, and (b) B-scan at a center frequency of 2.6 GHz</td>
<td></td>
</tr>
<tr>
<td>3.8</td>
<td>Synthetic metal corn seed of radius 0.024 m on sandy loam at 15% VMC and soil BD of 1.42 g cm(^{-3}) (a) B-scan at a center frequency of 1.6 GHz, and (b) B-scan at a center frequency of 2.6 GHz</td>
<td></td>
</tr>
<tr>
<td>3.9</td>
<td>GPR data collected from dry sandy-loam soil (a) GPR raw data and (b) Processed GPR data. Key: red arrows mark nominal corn seed positions, yellow arrows show a response which could be thought to be from the corn seed or clutter, and white arrow shows the approximate corn response. (t_1), (t_2), and (t_3) represents the time of flight to the corn seeds which also corresponds to the nominal depth.</td>
<td></td>
</tr>
<tr>
<td>3.10</td>
<td>GPR data collected from moist sandy-loam soil (a) GPR raw data and (b) Processed GPR data. Key: red arrows mark corn seed positions.</td>
<td></td>
</tr>
<tr>
<td>4.1</td>
<td>(a) A schematic layout of the soil boxes and (b) a 2-dimensional schematic side view of a box section with five synthetic corn seeds placed 0.0762 m deep, spaced 0.254 m apart in the soil. The schematic also shows the positive x-direction of the GPR antenna.</td>
<td></td>
</tr>
<tr>
<td>4.2</td>
<td>(a) Empty soil box with three partitioned sections (b) Soil box filled with soil and exposed stainless-steel seeds placed on top at 0.0762 m before covering them with soil (c) GPR cart rail track</td>
<td></td>
</tr>
<tr>
<td>4.3</td>
<td>GSSI SIR-20 System, 1.6 GHz and 2.6 GHz Antenna Controllers</td>
<td></td>
</tr>
<tr>
<td>4.4</td>
<td>Data collection (a) aluminum configuration inside soil box to minimize the effect of artificial reflections from side walls, (b) time-dependent gain manipulation.</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.5 Raw 1.6 GHz GPR data: (a) B-scan showing $t_{FW}$, $t_T$, and $t_d$ parameters and (b) A scan plot for the four medium synthetic metal seeds detected from the sandy-loam soil, (c) overlaying feature responses for the inidentification of common features, and (d) identification of the SCS response to avoid false positive. NB: Target A-scan is a representative of the three replicates and Rep is replicate.

Figure 4.6 Raw radargrams from a 1.6 GHz antenna (a) small, (b) medium, and (c) large SMS in non-saline sandy-loam soil.

Figure 4.7 Raw radargrams from a 1.6 GHz antenna (a) small, (b) medium, and (c) large SMS in non-saline loam soil.

Figure 4.8 The 1.6 GHz antenna mean comparison of amplitudes for SMS sizes in (a) non-saline sandy-loam soil and (b) loam soil.

Figure 4.9 The 1.6 GHz antenna mean comparison of the two-way travel time responses of different SMS sizes in (a) non-saline sandy-loam and (b) non-saline loam soil.

Figure 4.10 Raw GPR data from a 2.6 GHz antenna from non-saline sandy-loam at low soil VMC (a) small SMS, (b) large and (c) medium SWS.

Figure 4.11 The processed radargrams from a 2.6 GHz antenna collected from nonsaline sandy loam at low soil VMC (a) large and (b) medium SWS.

Figure 4.12 GPR data from a 2.6 GHz antenna in saline sandy-loam at low soil VMC (a) raw radargram, and (b) processed radargram.

Figure 4.13 Response Amplitudes of the 2.6 GHz antenna for small SMS, and SWS in (a) non-saline sandy-loam soil and (b) non-saline loam soil.

Figure 4.14 two-way travel time responses of the 2.6 GHz antenna for small SMS and SWS in (a) non-saline sandy-loam soil and (b) non-saline loam soil.
| Figure 4.15 | Response Amplitudes of the 2.6 GHz antenna for small SMS and SWS in (a) saline sandy-loam soil and (b) saline loam soil | 109 |
| Figure 4.16 | Two-way travel time responses of the 2.6 GHz antenna for small SMS and SWS in (a) saline sandy-loam soil and (b) saline loam soil | 110 |
| Figure 5.1 | Experimental setup (a) CS inside soil box section where seeds were buried at different planting depths and spacing in a single row, (b) top view of a single soil type in a box section, (c) parallel orientation of the GPR antenna | 121 |
| Figure 5.2 | Raw B-scan of stainless steel targets at the exact location of the CS in the sandy-loam soil. The red arrows show the exact positions of the steel targets | 122 |
| Figure 5.3 | GPR raw data of buried CS in sandy-loam, (a) represent radargrams from dry, (b) intermediate, and (c) moist group. The red arrows show the positions where CS should be in the image. The yellow arrows show the identified CS with faded hyperbolas. The white arrows show positions of the undetected CS (no hyperboles) or undiscernible responses or the responses that are either from CS or artefacts within the soil | 129 |
| Figure 5.4 | GPR raw data of buried CS in loam, (a) represent radargrams from dry, (b) intermediate, and (c) moist group | 130 |
| Figure 5.5 | A-scan background subtraction (BKG) | 132 |
| Figure 5.6 | Radargrams collected from the sandy-loam soil: (a) raw radargram from dry VMC group with one target visible, (b) processed radargram from dry VMC group with few CS targets visible, and (c) processed radargram from intermediate VMC group with mostly strong edges from artifacts | 133 |
Figure 5.7  Boxplots for temporal CS depths estimated using three dielectric permittivity models. Planting depth: shallow, moderate, and deep correspond to 3.81 cm, 6.35 cm, and 8.89 cm, respectively. (Topp-Mixing = Topp-Mixing model, SoilMixing = Soil mixing model and Topps = Topp’s dielectric model). The data presented is from the detected corn seeds only. ......................................................... 138

Figure 6.1  Map of the two plots A and B separated by a grassed waterway, courtesy of Google earth image, coordinates (42.021196 N, Longitude 93.773627 W). The arrow shows the direction of travel at seeding. . . 143

Figure 6.2  Adjusting the T-handle depth control of the planter to set the depths graduated 0.635 cm. ........................................................................ 144

Figure 6.3  Tractor setup. .................................................................................. 145

Figure 6.4  Corn depth layout (first six rows of the 12-row precision planter) . . 145

Figure 6.5  Row scanning with 2.6 GHz antenna directly on top of the closed furrow. ........................................................................ 146

Figure 6.6  (a) Closed furrows with side banks on each side, (b) Scanning perpendicular to the furrows. ......................................................... 147

Figure 6.7  (a) Measuring corn planting depth after seedling emergence, and (b) field measurement ......................................................... 147

Figure 6.8  Measured planting depth corresponding to the two downforces. . . 150

Figure 6.9  Corn plants in-row spacing. (a & b) represent good uniform spacing and (c) represent uneven or nonuniform seed spacing. .............. 152

Figure 6.10 Corn seed spacing corresponding to the 15.24 cm and 25.40 cm theoretical spacing. ......................................................... 153

Figure 6.11 Raw radargram with random hyperbolic responses and potential seed target. ......................................................... 154
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>6.12</td>
<td>Raw radargram showing no effective detection of seeds or significant</td>
<td>154</td>
</tr>
<tr>
<td></td>
<td>hyperbolic responses.</td>
<td></td>
</tr>
<tr>
<td>6.13</td>
<td>Raw B-scan</td>
<td>155</td>
</tr>
<tr>
<td>6.14</td>
<td>B-scan after applying the time-dependent gains.</td>
<td>155</td>
</tr>
<tr>
<td>6.15</td>
<td>B-scan of a 12-row precision planter collected perpendicular to the</td>
<td>156</td>
</tr>
<tr>
<td></td>
<td>furrows with a downforce of 354 N.</td>
<td></td>
</tr>
<tr>
<td>6.16</td>
<td>A-scan showing features that may have resulted from the compaction</td>
<td>157</td>
</tr>
<tr>
<td></td>
<td>zone of the pressing wheels or furrow path</td>
<td></td>
</tr>
<tr>
<td>6.17</td>
<td>A-scans represent features from 1.27 cm depth collected using a 354</td>
<td>158</td>
</tr>
<tr>
<td></td>
<td>N downforce in plot A.</td>
<td></td>
</tr>
<tr>
<td>6.18</td>
<td>A-scans represent features from 3.81 cm depth collected using a 354</td>
<td>159</td>
</tr>
<tr>
<td></td>
<td>N downforce in plot A.</td>
<td></td>
</tr>
<tr>
<td>6.19</td>
<td>A-scans represent features from 6.35 cm depth collected using a 354</td>
<td>159</td>
</tr>
<tr>
<td></td>
<td>N downforce in plot A.</td>
<td></td>
</tr>
<tr>
<td>6.20</td>
<td>A-scans represent features from 1.27 cm depth collected using a 451</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>N downforce in plot B.</td>
<td></td>
</tr>
<tr>
<td>6.21</td>
<td>A-scans represent features from 3.81 cm depth collected using a 451</td>
<td>160</td>
</tr>
<tr>
<td></td>
<td>N downforce in plot B.</td>
<td></td>
</tr>
<tr>
<td>6.22</td>
<td>A-scans represent features from 6.35 cm depth collected using a 451</td>
<td>161</td>
</tr>
<tr>
<td></td>
<td>N downforce in plot B.</td>
<td></td>
</tr>
<tr>
<td>6.23</td>
<td>Near field, far field, and compaction zones.</td>
<td>162</td>
</tr>
</tbody>
</table>
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Ndo boka.
ABSTRACT

Measuring planting depth is a challenge in precision seeding. Planting depth is commonly determined after seedling emergence and through a conventional method as described in DuPont Pioneer (2016), and ISO (1984), respectively. These approaches are disruptive to the soil seedbed, labor-intensive, time-consuming and large areas are not practical to survey. Therefore, a quality control technique to measure the planting depth after planting need to be established. The primary objective of this research work was to investigate the performance of nondestructive Ground Penetrating Radar (GPR) technology to detect buried corn seeds and measure corn planting depth. The GPR is a geophysical tool that employs material physical properties in a nondestructive manner to detect anomalies. GPR has been used in numerous agricultural applications with substantial success. Its application to detect corn seed is novel and may contribute significantly to precision seeding. Thus, a five-part research was conducted to meet the overall objective.

A theoretical review was conducted to identify subsurface sensing candidates and describe the techniques that could have application to the detection of corn seeds. Based on the merits, operational principles, and the suitability criteria of each technique, the GPR was recommended as the viable technology. The possibility and accuracy of using the GPR were investigated using numerical simulations, laboratory, and field experimental tests. An open-source software was used for numerical simulations. GPR antenna center frequencies of 1.6 and 2.6 GHz were examined. The effects of varied soil composition, bulk density, soil moisture contents, corn seed size, and corn dielectric properties were evaluated. The simulation results indicated that the GPR reflections provided substantial responses to locate synthetic and natural corn seed models in different soils with diverse conditions except in higher soil bulk densities and clay. At low soil moisture models, it was observed that am-
plitudes were extremely low which was attributed to the lack of dielectric contrast between the soil and the natural seed model. As expected, low clay content, bulk density, variable workable field soil moisture content was suitable for GPR wave propagation and detection. Higher antenna frequency provided higher target amplitude responses. Higher soil moisture relative to the natural seed model produced higher amplitude compared to drier soil.

Laboratory tests were conducted with four treatments: two soil types, salinity, soil moisture contents, corn seed simulants (stainless steel and plywood) and three simulant sizes. The simulants were buried at a constant depth of 7.62 cm. The 1.6 and 2.6 GHz antenna center frequencies were tested. Metal seeds were readily detectable in different soil conditions despite the seed size mainly using a 2.6 GHz antenna. However, at higher soil salinity and moisture contents, weaker hyperbola responses signatures were observed. Neither wood size was detected at higher soil salinity and moisture contents. However, the detection of wood seeds was possible in soil conditions that were below field capacity, using the 2.6 GHz antenna. The simulant sizes profoundly affected the detectability. The assessment of the 2.6 GHz antenna effectiveness was based on the percent Coefficient of Planting Depth Accuracy (CPDA) of ±0.5 cm. The CPDA was determined to be ±7.86% for the synthetic wood seeds.

Further laboratory tests were carried out using the Pioneer P0339AMXT PDR variety with an average moisture content of 10.1% using the 2.6 GHz GPR antenna frequency. In dry (less than 5% soil moisture content) soils some corn seeds were detected, while in intermediate (within 5% and 13%) and moist (greater than 13%) soils it was challenging to detect corn seeds. The dielectric permittivity used for calculating the depths were computed using Topp’s dielectric, soil mixing, and Topp-Mixing models. The Topp-Mixing model had the best CPDA of ±8.37%. Corn seeds were detected in controlled environment.

Field tests were conducted using the Pioneer P8542AMX-NJ02 PDR variety with an average moisture content of 13.2%. Corn seed spacing and planting depths were measured manually and with the 2.6 GHz antenna. The experimental design had three parameter
treatments consisting of; two downforce pressures, three populations, and three planting depths. The downforces significantly affected the planting depths and variability. The planting depth variability was more than the nominal resolution of the planter. Corn seeds were not reliably detected in the field. Hyperbolic features observed within the radargrams were random and inconsistent with the seed depth, and it was challenging to identify individual corn seed. There were horizontal features that were consistent and had similar two-way travel times to the bands observed in parallel and perpendicular radargrams. If the two-way travel times were the same, then it is highly likely that the bands in the parallel and perpendicular radargrams are from the same feature. Using the perpendicular to matchup with the parallel A-scans features that could represent the furrow were effectively identified. The work described shows that GPR could be employed to identify furrow features. The work presented in this dissertation necessitates more future research to establish the use of GPR as a quality control tool in precision seeding.
CHAPTER 1. GENERAL INTRODUCTION

1.1 Introduction

Corn is a valuable product in the US. It is mainly used for food, feed, and ethanol production. The ethanol produced in the U.S. is greatly influenced by the consumption of gasoline. Also, a substantial portion of the U.S. produced corn is exported which accounted for more than a third of overall corn exports worldwide: in the year 2017/18 corn worth $\approx 9.6\text{ billion} was exported. Also, on the report conducted by the USDA forecast a reduction in exports and domestic use of corn in the U.S while seed and industrial use are expected to increase. That is projected to be attributed to enormous quantities of corn being used for ethanol production with an approximate increase from 75 million to 7.1 billion bushels of corn (USDA, 2018). However, there are numerous challenges or limiting factors associated with corn production. Amongst other limiting factors to corn production that have been discussed extensively in literature, are the percent skips, seeding spacing and planting depth (Nielsen, 1993; Panning et al., 2000; Hanna et al., 2010; Kocher et al., 2011; Becks-Hybrids, 2014; Koller et al., 2014). In a publication by Nielsen (1993), he states that planting oversights can significantly haunt farmers the entire season, emphasizing the importance of seed spacing and planting depth in crop production. Growers spend money on corn seeds to sow and not to find themselves replanting the field later due to mistakes. In such cases, planting mistakes may be thought of as permanent. Nielsen also alludes that yield can potentially be affected by uneven emergence even well before there is any significant growth. Planting depth is a challenging aspect to control without any monitoring systems to assist with correct placement of the corn seeds.
Reeves and Cox (2013) indicated that corn seeds are expensive and can influence farmers to reduce higher seeding rates and widen seed rows to decrease higher expenditure or cost on corn seeds. However, with high demands of corn in the U.S. farmers are incentivized to higher seeding rates (high plant density) for maximum corn production. Precision seeding is a vital concept in seeding management practices as it implies the correct amount of seeds can be placed at the right time and right spatial placement (spacing and depth) in an open trench. The recommended corn seed planting depth at field capacity (correct moisture zone) range from 3.81 cm (1.5 in.) to 5.08 cm (2.0 in.), for expedited germination, maximum emergence rates, and strong root establishment. However, field conditions may vary markedly in soil water content. Therefore, in droughty field areas, corn seed may be planted deeper to 7.62 cm (3 in.) to 8.89 cm (3.5 in.) in clay soils, 10.16 cm (4 in.) to 11.43 cm (4.5 in.) in loam soils, and 12.7 cm (5 in.) to 15.24 cm (6 in.) in sandy soils. In cases where soil water content is slightly above or adequately at field capacity shallow planting would be recommended (Elmore, 2013; Hanna, 2013).

Accurate seeding has over the years been and is still prioritized to maximize corn production and prevent adverse effects such as (1) difficulties in survivability of the emerging plant, (2) weak root formation, (3) uneven seedling emergence, and (4) low yield at harvest from being prevalent (Carter et al., 1990; Yoder et al., 2001; Abendroth and Elmore, 2006; Karayel and Ozmerzi, 2008; Elmore et al., 2014; Zhang et al., 2015). Efforts are made to integrate advanced technological methods that work against the adverse effects brought about by the planting depth inadequacies (Hanna et al., 2010; Becks-Hybrids, 2014). The inability to implement variable planting depth and/or maintain uniform corn seeds sowing is a critical problem in precision planters which introduces a major hurdle in precision farming. But, with the advent of technologies, precision practices and techniques to improve corn production could be achieved.
1.1.1 Planting depth control

Downforce has been in the core center for controlling planting depths on precision row planters. Numerous technologies such as pneumatic (e.g., Precision planting 20/20 Airforce SeedSense) and hydraulic (e.g., Precision planting 20/20 Airforce SeedSense and DeltaForce) down pressure force systems have been researched, tested and implemented as an effort to maintain an adequate and consistent planting depths. These down pressure force mechanisms are closed-loop controlled to maintain required force which keeps the planter in contact with the soil (incorporate on-the-go adjustments). The two systems mentioned greatly vary in their operation which directly impacts potential yields. The systems are designed to adjust depths according to the variation in field topography. A significant discrepancy between the pneumatic and hydraulics have been reported regarding the reaction time. The pneumatic system was reported to be twenty times slower than the hydraulic counterpart which only takes one second to adjust according to the topography (Becks-Hybrids, 2014). In that time delay, seeds can be landing on undesirable or unconducive places which do not promote germination. However, with these systems in place, seeds can either be planted shallower with less downward force or deeper with excess downward force causing side compaction, germination and seedling emergence difficulties. The latter could also be attributed to in-field soil variations or surface undulations which makes the overall downforce challenging to predict.

1.1.2 Planting depth Variability

Reeves and Cox (2013) recommended that variable seeding rates should continually be practiced according to in-field soil water conditions. Techniques have been developed as an effort to place corn seeds at variable seeding depth depending on soil water content at field capacity. Price and Gaultney (1993) developed a near-infrared (NIR) sensor to determine the soil matric potential. The matric potential is the pressure that holds the water in the soil and signifies the suction that must be overcome by the seed or plant to absorb the water
from the soil as stated by Price and Gaultney (1993). The NIR sensor was developed to determine the soil matric potential and hence adjust the corn planting depth accordingly. In the developed algorithm, two planting control were implemented: (1) planting shallow or at the current planting depths when the soil was at or above field capacity and (2) planting deeper when the soil matric potentials were low. The NIR was tested both in the laboratory and field with promising results at varying matric potentials.

René-Laforest et al. (2014) developed and tested an automated variable depth system, that controlled planting depth based on soil water content in the field, measured from a capacitance-based soil moisture sensor. The corn seeds were placed at variable planting depths and the corn crops germinated accordingly with strong and denser root establishment. These techniques have been tested but not yet commercialized for mass production. The soil matric potential or moisture content measurement technologies are relatively new in precision seeding. Nonetheless, these technologies do not measure corn planting depth instead they exploit spatial moisture content to place the seeds in the furrow.

1.1.3 Motivation

Currently, corn seed planting depth is acquired through the conventional method, which is markedly disruptive to the soil seedbed, labor-intensive, time-consuming, susceptible to error, and large areas are not practically possible to survey. Moreover, the conventional method is highly likely to displace sown seeds from their original placement. The conventional method is as described in the ISO (1984) whereby soil layers covering the seed are removed by flat scraper graduated in millimeters, simultaneous searching to expose the seed top surface. The seed depth is then measured against the side of the box as shown in Figure 1.1. The second approach of determining planting depth is after seedling emergence. Seedlings are excavated, and depths measurements are taken as shown in chapter 6 following DuPont-Pioneer (2016) procedure. The measured depths are also compared with theoretical depths set on a planter. The disadvantage with approach is that planting mistakes are real-
ized late or after germination has taken place. The acceptable seed depth is the measured depth that is within the theoretical planting depth range (see above).

![Conventional method of quantifying sown seed planting depth (ISO, 2018)](image)

Figure 1.1  Conventional method of quantifying sown seed planting depth (ISO, 2018)

However, the need to deploy an effective, efficient, and cost-effective technological tool to measure seed planting depth in a closed trench is mandatory for correct placement of corn seeds in a furrow and precision farming management systems. The ability to determine exact planting depth for a closed loop active control system would provide accurate control of planting depth. A review of potential candidates to detect corn seeds and quantify planting depth has been conducted, and in the final remarks, the ground penetrating radar (GPR) was recommended to be a practical approach to advance the research-work herein (see chapter 2). Thus, this thesis proposes a noninvasive GPR for the detection and estimation of planting depth in different soil conditions.
1.2 Research Objectives

The primary objective of this research work was to investigate the performance of non-destructive Ground Penetrating Radar (GPR) technology to detect buried corn seeds in different soils, and quantify seed planting depth.

1.2.1 Specific objectives

1. to develop a 2D GPR model using gprMax to evaluate the potential of GPR for detection of seeds placed at different depths and investigate the effect of soil parameters on dielectric properties and their subsequent effect on GPR waves detection.

2. to use GPR to locate and quantify seed planting depth on different soil types, soil moisture content and soil salinity in the laboratory and field.

3. to evaluate analytical and statistical methods and propose a suitable approach for determining planting depth.

1.2.2 GPR background

The GPR is a sophisticated instrumental device used to measure quantities and detect discontinuities to map the subsurface targets hence providing accurate depth profiles for features within the subsurface or material under test (MUT). These waves are application specific and behave in a unique fashion to each other, governed by the bandwidth and wavelength. The fundamentals of the GPR waves are predicated on electromagnetic (EM) theory. The discovery of EM waves date back more than half a century ago and Maxwell has demonstrated that EM waves have the electric and magnetic components that can propagate in free space at the speed of light (Maxwell, 1864). There are different types of EM waves which include radio waves, visible light and gamma rays et al. In the 1900s, Radio waves at that time were only propagated above and along the ground surface, at which time more experimentations were conducted to understand how radio waves interact with other...
mediums. The first subsurface experimental results reported by the United States Air Force (USAF), were over Greenland ice sheets, where a pulsed radar registered incorrect height recording (at low altitudes near the icy body) on the altimeter (Waite and Schmidt, 1962; Novakova et al., 2013), this was the first realization that radio waves can propagate through ice, thus, lead to the development of radio instruments which were designed to measure ice thickness (Evans, 1963). This gave researchers a perspective to explore avenues to utilize radio waves by conducting further purposeful experiments.

The study of the lunar subsurface in preparation for Apollo mission program followed, of which the authors reported that the lunar subsurface had electrical characteristics similar to that of ice (Stillman and Grimm, 2007; Annan, 2009; Novakova et al., 2013). Thus, two dielectric properties were realized (1) permittivity and (2) ionic electrical conductivity. In 1970, extensive literature and experimentation on the material electrical properties were conducted to expand radio waves applications. Apart from ice, radio waves were further extended to subsurface evaluation as a result of the established dielectric properties. In the late 1978’s radio waves were employed in pedologic studies. Doolittle and Collins (1995) used GPR waves in pedology research, for soil classification, identify different geological layers, composition, horizon depths, and results from the study showed accurate predictions of soil information which agreed with the soil chart classification from the National Cooperative Soil Surveys program.

In recent years, however, the advent of computers and available technologies has expedited the growth of radio waves technique (Annan, 2009; Jol, 2009), it has immensely evolved, with myriad geophysical applications to date. The technique is routinely used in various disciplines, such as archeology, geology, and electrical engineering, structural engineering, civil engineering, military, transport (road assessment) and agriculture, etc. as a noninvasive evaluation technique in subsurface exploration applications (Pîrnău et al., 2015). The GPR technique has proven to be of great value to agricultural engineering (see Chapter 2 subsection 2.2.2, Ground penetrating radar) and further purpose-built data acquisition
GPR devices are now designed and developed which means a researcher now has a full range of GPR devices to choose from to conduct respective experiments. Since soils and corn seeds are dielectrics, the utility of the GPR technique for the corn seed detection application could advance precision corn seeding.

1.2.3 GPR theory and constitutive properties

The GPR uses the radar spectrum and is a technique that exploits the physical properties of the subsurface using electromagnetic (EM) waves. The use of EM waves is diverse mainly with advantages and disadvantages depending on the selected system parameters. The system parameters are decided at the initial framing and design process which is also a determinant of the application (the GPR designs dictates the application and the type of subsurface targets to be mapped). When designing a GPR system, the most primary parameter to consider is the system operating center frequency. The operating center frequency governs the wave propagation velocity, attenuation through the ground, and image resolution. To offer effective performance of the EM waves, the device must be capable of satisfying the following conditions: (1) penetrating to desired depths, (2) distinguishing the target from the host and (3) providing desired sensor resolution which is mostly dependent on the EM wavelength (equation 1). The design component of the GPR system is not covered in this thesis because an off-the-shelf GPR system was used in the investigation. For readers interested in GPR design, an excellent explanation is provided by Jol (2009). However, the explanation of the theory of EM waves propagation and interaction with subsurface to map targets is provided hereafter.

The GPR can map different subsurface target sizes and shapes such planar surface, cylindrical, cuboidal (Hasan, 2015), and spherical objects. The latter is only achievable when a substantial dielectric discontinuity exist within the surveyed subsurface or material under test (MUT). A typical GPR antenna system has a transmitter to pulse waves into the ground and receiver to capture reflected EM waves, as shown in Figure 2.2. The EM
waves are transmitted at a prescribed frequency into the ground, and at a proximal height predetermined by the operator, preferably in contact with the ground to minimize EM energy loss. As explained by Jol (2009), there are two ways to deploy GPR sources (1) contact with the ground (low EM energy losses) and (2) non-contact or air-launched GPR (high EM energy losses). A pulsing incident wave hits and enters the ground and assuming a lossy dielectric media (substantial disparity in physical or dielectric properties at the interfaces), some EM waves are reflected, diffracted (i.e., bending of waves around an object), and refracted further into the ground (i.e., propagate to greater depths until all the EM wave energy has been dissipated and absorbed) (Sadiku, 2010).

The propagated EM waves occur in a sequence of pulses that have cone-shape footprint. The width of the cone footprint depends on the wavelength size which depends on the frequency (narrow cone footprint means higher operating center frequency and conversely, wide cone footprint lower operating center frequency), as shown in Equation 1.1. Due to the cone nature of the transmitted wave, the antenna does not have to be directly on top of the target as the energy can still reach the target before the center point of the antenna coincides with target mid-point.

The transmitted wave attenuates proportionally to the magnitude of the MUT electrical conductivity and as a function of distance or depth traversed (Huisman et al., 2003; Jol, 2009). The radiated GPR waves propagate and dissipate energy ($E$) radially ($r$) as it travels far from source or encounters obstacles (dielectric anomalies), with an exponentially increasing cone footprint traversing through the MUT. The phenomenon follows GPR energy dissipation law, defined in Equation 1.2. When radius increase to greater depths ($R$), where $R \gg r$ then the energy at that instance is very small (Jol, 2009; Amiri, 2016).

$$\lambda = \left(\frac{c}{f}\right)$$  \hspace{1cm} (1.1)

where $c = 3 \times 10^8$ m s$^{-1}$ is the speed of light in a vacuum, $\lambda$ is the wavelength (m), and $f$ is the nominal center frequency (GHz).
Energy dissipated = \( \left( \frac{E}{4\pi r^2} \right) \) \hspace{1cm} (1.2)

Moreover, as waves bend and accompanied by intermittent spreading / backscatter from a point target, the phenomenon is referred to as the diffraction of waves, which in GPR theory creates the hyperbolic response observed within the GPR image, Figure 4.5. The orientation of the GPR antenna is essential during subsurface scanning. GPR antenna is polarized therefore the long axis of a target have to be parallel with the polarized electric field for substantial subsurface mapping. However, for equidimensional small targets, the antenna orientation is less critical. Therefore, mapping such targets would be predicated on the wave footprint size (Amiri, 2016).

1.2.4 Dielectric materials, properties, and polarization

Dielectric in its simplest definition refers to a non-conducting material. There are several, well known dielectric materials such as air, wood, plastics, water, and soil et al. These dielectric materials consist of polar molecules (partial negative and positive charges) that can be effectively polarized by an alternating electric field. During dielectric polarization the charges are shifted and aligned with their opposite charges, leaving a neutral environment between separated charges. That leads to an overall velocity decrease of the traversing electric field through a material. Further, the electric field strength reduces and upon completion of charge alignment leads to a zero net electric field across the material. In the study of dielectric materials, the focus is on electric, magnetic energy storage and energy dissipation within a material. A dielectric material is defined by the dielectric permittivity (F m\(^{-1}\)), permeability (H m\(^{-1}\)), and electrical conductivity (S m\(^{-1}\)) (Annan, 2009; Jol, 2009; Sadiku, 2010).

In general, most dry soils relative dielectric permittivity ranges from 2 - 6 (Daniels, 2000). Water-saturated soils have higher dielectric permittivity. That is supported by the theory of heterogeneous dielectrics where fictitious data generated were compared with experimen-
tal data, and water was found to have a significant effect on material dielectric permittivity (Pearce et al., 1973; Wobschall, 1977). Water has a relative dielectric permittivity of approximately 81. Moreover, the dielectric permittivity of a material depends upon the frequency, as depicted in Figure 1.3, the material constituents or composition (particle size and volume fraction), material physical properties (bulk density).

The effective dielectric permittivity, \( \epsilon \), allows electric charge to be stored in a material. The charge stored because of the applied electric field depends on the magnitude of the dielectric permittivity of the material. The larger the relative dielectric permittivity, the higher the electric charge storage and the converse is true (Norimoto, 1976). The real dielectric permittivity (\( \epsilon' \)) is given as a product of the relative dielectric permittivity (\( \epsilon_r \)) and dielectric permittivity of free space (\( \epsilon_0 \)): \( \epsilon' = \epsilon_r \epsilon_0 \). The effective dielectric permittivity (\( \epsilon \)) is given as a complex function, to represent a lossy media. The imaginary component of the function represents the loss factor (\( \epsilon'' \)) within a material: \( \epsilon = \epsilon' - j \epsilon'' \).

Permeability, \( \mu \), allows the magnetic energy to be stored within a material. Permeable materials are easily magnetized under the influence of the alternating magnetic component of the EM pulses. Magnetic permeability can also be expressed as a complex number, but in mediums like soil, the magnetic losses are often small and difficult to quantify at the interface. Therefore, the imaginary part of the permeability is omitted. The permeability property is expressed as the product of relative magnetic permeability (\( \mu_r \)) and permeability of free space (\( \mu_0 \)): \( \mu = \mu_r \mu_0 \) (Neal, 2004; Jol, 2009; Sadiku, 2010).

Electrical conductivity, \( \sigma \), defines a material that effectively conducts the electric component of the EM wave. Soil electrical conductivity arises from ionic concentration capable of shifting and orient to electric field component. The property contributes to high EM energy absorption, dissipation, attenuation (ohmic losses) or total reflectance of the electric field. Soil electrical conductivity is influenced by the soil soluble salts, organic matter, bulk density, soil moisture, and clay content. Mohamed (2006) work shows that an increase in soil moisture and / or clay content has a profound effect on overall soil conductivity, as
shown in Figure 1.2. The electrical conductivity is expressed as a complex function: $\sigma = \sigma' - j \sigma''$ with real $\sigma'$ and imaginary $\sigma''$ electrical conductivity components. These three properties govern EM waves absorption (attenuation), dispersion, phase shift, the reflectance at interfacing boundaries and the overall propagation velocity (Orfanidis, 2002).

![Figure 1.2](image.png)  
**Figure 1.2** Effects of increasing soil water and clay contents on electrical conductivity

Polarization mechanisms discussed in the literature include electron (atomic), molecular (nuclei motion), orientational (dipolar molecules rotation, i.e., water molecules are permanent dipolar), and interfacial (drifting of ions) polarization, shown in Figure 1.3 (Chen and Or, 2006). All these polarization mechanisms have their cut-off frequency, thereby an increase in frequency will cause some mechanisms to be ineffective. Thus, the actively effective dielectric mechanisms will have a contribution effect to the dielectric permittivity, Figure 1.3 (Saarenketo, 1998; Jonscher, 1999).

For polarization to effectively occur, the frequency must be smaller than the frequency at the relaxation time. Beyond relaxation time-frequency, dielectric losses are prevalent, and the effective dielectric permittivity starts to decline rapidly with an increase in frequency whilst the dielectric loss-factor increases. This research focuses on using low polarization center frequency approximately less than 3 GHz. According to Figure 1.3, the interfacial polarization would play a crucial part in this study. Soils have varying interfacial facets
attributed to their natural physical or electrical properties as explained above, the difference in interfacial properties contribute to the amount of EM wave reflection, refraction, and overall absorption. The EM wave center frequency is a factor that needs careful attention when selecting an antenna for a task. In this research study, selection of the antenna frequency was dependent upon the penetration depth to be assessed, target size and the resolution needed. Targets to be mapped (corn seeds) were small and buried at shallow depths. Therefore, a high center frequency GPR antenna was more suited to achieve the project goal.

1.2.5 GPR data acquisition modes and wave propagation

A typical GPR system can either have a variable or fixed separation distance. These are the four modes that the GPR can operate in (1) trans-illumination, (2) single offset reflection, (3) multiple offset reflection and (4) common offset reflection survey (fixed separation). Trans-illumination is commonly used in borehole surveys whereby the transmitter
and receiver are synchronized with each other to detect target geometry, and the single offset reflection measurements are acquired at single common point whilst the transmitter and receiver separation distance are simultaneously varied. For a multiple offset reflection, a transmitter is fixed at one position, and the receiver position is varied on a stepwise pattern, keeping a common midpoint. At each time, the reflections are recorded (amplitude strength and two-way travel time). COMMON OFFSET REFLECTION survey the transmitter and receiver separation distance is fixed (Jol, 2009). Most GPR systems use the common offset reflection survey mode. The advantage of using a common offset reflection survey over the other acquisition methods is that the system has a fixed geometry, which makes surveying and mapping subsurface more rapid. The method also offers an improved signal-to-noise ratio. The time delay and reflected amplitude provide information such as the total attenuation, velocity, depth and impedance of the mediums involved. Reflections only occur when discontinuities in electrical properties exist, and the magnitude of the reflection is dependent upon the magnitude of the electrical property change along the propagation path. Therefore, the bigger the change would mean a strong reflection (Davis and Annan, 1989; Annan, 2009; Jol, 2009; Kang and Hsu, 2013).

Mostly EM waves are application specific, and the EM signals commonly used in reflection surveys are propagated in two ways isotropically or anisotropically. In most common GPR instruments, the source antennas (at low frequencies) are unshielded, and signals are propagated isotropically. This phenomenon renders the waves to be weak in all directions. Hence the resolution to the target could be compromised due to the wavelengths elongation which eventually varnishes. Weaker EM waves have limited ranges. However, shielded antennas are effective, and operation frequencies are higher (MHz to GHz) and signal directivity and resolution optimal. The directivity can also be influenced by the ground traversed by the EM wave. The shielding process selectively suppresses some waves and at the same time enhances the directionality of waves of interest. Also, interference from other EM sources are minimized, Figure 1.4 (Jol, 2009) and target resolution improved at higher center fre-
quencies. Figure 1.5a & b, show directivity of EM wave propagation for an unshielded and shielded antenna, respectively (Huisman et al., 2003; Jol, 2009).

Figure 1.4  Shielded Transmitter and Receiver antenna from external signal interference. TX and RX represent a measured signal

Figure 1.5  Wave directionality of the (a) unshielded and (b) shielded antenna

As GPR waves propagate deeper into the ground are likely to suffer from high attenuation as depicted in Figure 1.6. To compensate for losses as the wave traverses into the ground a time-dependent gain function is used shown in Figure 1.7. The time gain function applies
variable gain points due variation of subsurface attenuation to enhance mostly the weaker waves that are at greater depths. Moreover, doing so equalizes the amplitudes (Jol, 2009).

![Diagram of equal reflectivity earth, low and high attenuation](image)

**Figure 1.6** Propagation and Reflection of layered earth model; equal reflectivity horizons, low and high attenuation

![Diagram of time-dependent gain function manipulation](image)

**Figure 1.7** Time-dependent gain function manipulation to enhance the deep attenuated waves in the subsurface (a) Low resolution GPR A-scan before gain correction, (b) time-varying gains that compensate for weak amplitudes to improve resolution, and (c) High resolution GPR A-scan before gain correction.

1.2.6 **GPR data visualization and processing**

The GPR data can be visualized in one of the three ways (1) A-scan, (2) B-scan, and (3) C-scan. These GPR scans convey information about the surveyed MUT. The conveyed
information within the data is the amplitude strength and the two-way travel time or time of flight, measured from contrasting features within the MUT. An A-scan is a single line scan that is defined by the response amplitude as a function of time referred to as the two-way travel time. The A-scan is recorded from a single fixed antenna position (example Figure 1.7a). A combination of several A-scans creates a B-scan which is a 2D gray-scale image also commonly referred to as the radargram (example Figure 1.8). A combination of B-scan images leads to a C-scan image (3D image).

The B-scan is commonly used for visualization, processing, and interpretation. Also, in the B-scan, there are several phenomena that can be observed due to the interaction of the transmitted wave and EM properties of the MUT. These are multiple reflections (intermittent scattering), horizontal ringing, and reverberation. These occurrences may be entirely noise features in B-scans. Multiple reflections are attributed to the substantial variation of dielectric discontinuities within the MUT, horizontal ringing is usually the ridges visible along the B-scan, and reverberation is considered an event where the transmitted wave creates multiple reflections which are not as strong but absorbed within the MUT as the waves interact with the particles. Clutter within the MUT and noise from surroundings may

Figure 1.8 B scan
exacerbate the noise levels within the B-scan. A portable shielded GPR antenna from Geo-
physical Survey Systems, Inc., was used in this study. The coupling losses were minimized
by directly moving the antenna slowly (low velocity) in contact with the soil to maximize the
directionality of the wave into the soil. Moreover, it was necessary to calibrate the survey
wheel, to accurately map the positions of the buried targets in the soil.

A great deal of practice or experience or knowledge about GPR imagery is imperative for
both the processing and interpretation of the data. There are several tools that are primarily
designed to process and analysis GPR data. These are the RADAN 7 (software package
proprietary to the Geophysical Survey Systems, Inc.), the matGPR (MATLAB package),
and a FORTRAN package. The packages have built-in functions that are used to manipulate
the image through basic or advanced processing, editing B-scans, extraction of features from
the B-scans, and transforming the GPR data to improve visualization and interpretation of
the data. The initial step of processing GPR raw data is to edit the information to reduce
or eliminate inconsistencies in processing. The editing process involves adjusting the time-
zero (aligning the instance where the wave enters the MUT with the zero mark), cutting
and discarding out part of the data that is not needed. Gain manipulation and denoising
by applying filters (i.e., clutter removal, suppress background noise filtering) are more on
the advanced processing. However, precautional measures need to be taken because either
can distort the quality of the image. The explanation above is summarized in processing is
shown in Figure 1.9, after Jol (2009).
1.2.7 GPR wave velocity correction

The GPR wave propagation velocity \( (v) \) is mainly influenced by the soil dielectric permittivity \( (\varepsilon) \), as shown in Equation 1.3. The soil dielectric permittivity is governed by soil volumetric moisture, soil composition, free space parameters, and the bulk density.

\[
v = \left( \frac{c}{\sqrt{\varepsilon}} \right)
\]  

(1.3)

Reasonable fidelity empirical models developed by Topp et al. (1980) and Peplinski et al. (1995) are used to predict the soil dielectric permittivity based on respective soil physical properties. These models are used to correct for wave propagation velocity prior to estimating planting depth. The GPR wave velocity is covered in detail in Chapter 4 through Chapter 6.
1.3 Dissertation Organization

The organization of this dissertation is presented on this current chapter. This dissertation is organized into seven chapters which follow the manuscript format, and all chapters are standalone with their cited materials at the end of each chapter except for the conclusion chapter which summarizes the findings of the whole dissertation. The current chapter provides general overview of the research problem as it pertains to the agricultural corn production and precision seeding. Moreover, the justification of the problem, overall objective, and the GPR literature review relevant to subsurface detection application are provided. Chapter 2, Chapter 3, Chapter 4, Chapter 5, and Chapter 6 are manuscripts. These manuscripts address the overall objective of this dissertation. Chapter 2 provides a review of potential sensing candidates that could have application to subsurface seed detection, depth estimation, and with the possibility to integrate it for on-the-go planting performance analytics. Chapter 3 describes a 2D gprMax simulation study that investigates the effects of soil electromagnetic properties on GPR waves. In the simulation a conventionally fixed offset gprMax antenna model was used to evaluate the possibility to detect subsurface corn seeds using the GPR as a nondestructive sensor with a goal of measuring planting depth. Chapter 4 demonstrates the experimental tests conducted using synthetic corn seeds. The synthetic corn seeds were made of metal (stainless steel) and wood (poplar) and had three different sizes, respectively. The seeds were buried 0.0762 cm (3 in) deep. Two GPR antennas of center frequency 1.6 GHz and 2.6 GHz were tested. The design of experiment conducted was proof of concept to practically evaluate the GPR effectiveness in detecting shallow-buried synthetic corn seeds (SCS) in sandy-loam and loam soils and discusses the statistical model for possible detection of real agricultural corn seeds. Chapter 5 is an extension of the statistical model explained in Chapter 4. The chapter describes the experimental research using real corn seeds buried at three different depths (3.81, 6.35, and 8.89 cm) and two spacing (15.24 and 25.4 cm) in sandy-loam and loam soils. A 2.6 GHz GPR antenna was used for data collection. Chapter 6 describes field experimentation. The
work focused on quantifying planting depth manually (after seedling emergence) and with a 2.6 GHz GPR antenna. Also, features that could potentially represent the furrow path were identified. Chapter 7 provides the general conclusion of the five-part research and potential future research suggestion to achieve seed detection and corn depth quantification.

1.4 Publications or Submitted Manuscripts

The work that has been conducted in the period of my PhD include submitted papers for possible journal article publication, and conference papers.

1.4.1 Submitted papers

1. Authors: (K.O.M. Mapoka\textsuperscript{a,1}, S.J. Birrell\textsuperscript{a}, and M. Tekeste\textsuperscript{a}). A comprehensive survey of nondestructive sensing technologies for the detection corn seeds in a closed trench and measuring planting depth to augment the conventional method: Status - Under review. \textsuperscript{a}Department of Agricultural and Biosystems Engineering, Elings Hall, Iowa State University, Ames, Iowa, USA, 50011, \textsuperscript{1}Corresponding author

2. Authors: (K. O. M. Mapoka, S. J. Birrell, M. Tekeste, B. Steward, D. Eisenmann). Using gprMax to model ground penetrating radar (GPR) to locate agricultural corn seed as an attempt to measure planting depth. Status - Under review

3. Authors: (Kenneth O.M. Mapoka\textsuperscript{a,*}, Stuart J. Birrell\textsuperscript{a}, David J. Eisenmann\textsuperscript{a}, Mehari Tekeste\textsuperscript{a}, and Huaiqing Wu\textsuperscript{b}). Experimental Approach to Quantifying Synthetic Corn Seed Planting Depth Error Using a Ground Penetrating Radar. Status - Under review. \textsuperscript{*}Corresponding author, \textsuperscript{a}Department of Agricultural and Biosystems Engineering, Elings Hall, Iowa State University, Ames, Iowa, and \textsuperscript{b}Department of Statistics, Snedecor, Iowa State University, Ames, Iowa
1.4.2 Referenced conference articles


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Becks-Hybrids (2014). *Practical Farm Research (PFR) Book*. Beck’s Hybrids, Atlanta, IN.


CHAPTER 2. A COMPREHENSIVE SURVEY OF NONDESTRUCTIVE SENSING TECHNOLOGIES FOR THE DETECTION OF CORN SEEDS IN A CLOSED TRENCH AND MEASURING PLANTING DEPTH TO AUGMENT THE CONVENTIONAL METHOD

A paper modified from a manuscript submitted in the Journal of Computers and Electronics in Agriculture

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Abstract

Due to the importance of planting depth on yield potential, a number of pressure based active planter depth control systems are commercially available. These systems actively control downward pressure on the planter units based on a target pressure setting. However, the necessary target pressure can change significantly depending on spatial and temporal conditions. The real-time planting depth sensing is required to enable closed loop control of planting depth. Sensor based, closed loop control would significantly improve the accuracy of these pressure based active control systems, and significantly improve the potential yield and economic benefits of planter depth control systems. The primary objective of this review was to evaluate nondestructive sensing technologies that may be used for corn seed detection. Thereby, enabling determination of planting depth in a closed trench. The reviewed
sensors are commercially available, and many are currently used in various agricultural applications for subsurface nondestructive measurements. Principal factors that are covered include; suitability for the application, operational requirements, and sensor advantages and limitations for soil subsurface detection. The reviewed nondestructive sensing technologies incorporate on-the-go strategical principles that could potentially provide real-time planting depth data at planting or post-planting. Ground Penetrating Radar (GPR) was recommended as a viable candidate for corn seed depth sensing but there is no one technique that can be conclusively identified as the best technology.

**Keywords**

Planting depth, corn seed, subsurface, GPR, dielectric permittivity, planter kinematic

### 2.1 Introduction

Planting Depth (PD) is an essential factor in agricultural production and has a major influence on plant germination and final crop yield. Successful emergence is dependent on the energy stored within the seed and energy required for the seedling to force its way to the surface. Deeply planted seeds may not have sufficient energy to reach the soil surface and die before emergence. For the shallow-planted seeds, the crown may develop above the soil surface leading to an exposed root system. In this case, the young plant can be blown or washed away, by strong wind or water currents. Moreover, the corn seeds on the soil surface may encounter extreme difficulties to extract adequate moisture content from the soil to germinate (Sistler, 1991). Researchers have identified the recommended PD ranges for different crop species, based on seed type and size, soil type, texture, tilth, temperature, nitrates, soil pH, and moisture conditions (Nielsen, 2001; René-Laforest et al., 2014). Therefore, a number of companies are developing planters which actively control the downward pressure on planter units to control PD. The challenge is to determine the relationship between down pressure and actual PD under variable field conditions (Hanna et al., 2010). When soils are level and uniform across the field, PD may be a lot easier to
maintain. However, soils are never uniform, nor level. The soil surfaces consist of rapidly variable undulations, soil types, and structures across a field, then maintaining a consistent PD becomes a difficult task (Sistler, 1991).

A recent study published by Becks-Hybrids (2014), reported on field trails of active pressure control systems on both PD and corn yield. The results showed that farmers are facing approximately 20% to 30% losses of yield when planting shallow (0.5-0.75 in.) compared to the control planting depth (1.75 in.). Also presented in the study are measures to control PD by monitoring the down-force pressure. Doerge et al. (2015) reported yield losses of 5% to 9%. Hanna et al. (2010) conducted a related study where the down-force or load was significantly correlated with the emergence rate at different soil conditions. The active control of down pressure to influence seed PD is becoming increasingly common. However, the challenge is determining the optimum down pressure setting under highly variable soil conditions to achieve the optimum depth. The active control systems are open-loop control systems with respect to PD. Although the active control systems are very accurate in maintaining the target down-pressure, open-loop depth control may not achieve the correct PD due to the inconsistent relationship between down pressure and PD. The ability in determining actual seed depth for a closed loop active depth control system would increase active depth control accuracy at planting.

In agricultural corn production, the detection of seeds nondestructively in a closed trench is important, since PD is directly related to corn productivity and economic return. Implementation of the appropriate nondestructive seed detection technology for measurement of PD in a closed trench, must consider several factors including the soil physical properties, sensor type, seed geometry, and other inferences within the soil matrix. Nondestructive technologies for the subsurface measurements have been implemented in various agricultural applications such as determination of soil water content, salinity, texture, clay, and locating agricultural drainage pipes and in forestry investigations (root biomass evaluations). This paper describes different nondestructive approaches that may be applicable to corn seed
depth detection. The overall objective of this publication was to review sensor technologies that could be successfully used to detect and quantify seed PD in a nondestructive manner. The technologies reviewed emphasis on on-the-go methods that can provide real-time data at planting.

2.2 Measuring Corn Seed Planting Depth Strategies

The conventional method to measure seed PD involves manually digging in the seedbed, searching to expose seeds and measuring PD with a ruler or tape. The method is destructive in nature, susceptible to measurement variability due to human errors, time-consuming, and unsuitable for repeatable real-time measurements. The review focuses on two different sensing technologies, the first based on planter kinematics sensing and the second based on contact or non-contact soil subsurface detection methods (Figure 2.1)

Figure 2.1 Classification of sensing technologies for possible detection of corn seeds in a closed trench

2.2.1 Planter kinematics

Theoretically, the PD can be monitored using sensors to measure the relative position and / or rotation of linkages within the planter frame, and measurement of the relative position of the planter frame above the soil surface datum. If the planter linkage geometry is known, the tolerances within the linkage mechanisms are sufficiently accurate, and the
relative position of the soil surface datum is measured, kinematic calculations could be used to determine the PD. However, the measurements are profoundly influenced by tolerance within the linkages and planter vibrations. Planter vibrations and kinematic movement between linkages are dependent on the soil characteristics, field topography, planter geometry and operational settings, including soil type, texture, tilth, moisture and compaction, prior tillage operations, operational speed and acceleration of the machine.

Fields are not perfectly flat and do not have the same soil structure across the entire field. A typical field has a variety of different soil types and textures. If the planter is not set up to adjust the downforce pressure force according to in-field conditions, then the seeds may end up being planted improperly. Either too shallow when downforce is insufficient or too deep with excessive downforce that may compact the seedbed and impede seedling emergence or development of necessary root structure. Some modern planters are equipped with active downforce pressure control systems (based on pneumatic or hydraulic actuators) designed to ensure that planter row units maintain good soil contact and control the downforce on the planter units. These systems control the down-force required to maintain a constant margin load at the soil surface contact. The margin load is the monitored force that ensures there is sufficient ground contact and it is measured by strain gauge sensors attached to the depth control pin fulcrum (Sistler, 1991). Depending on the measured margin load the downward pressure force can be adjusted to maintain the set margin load, and preventing the margin load to go to zero or exceeding the set load. This is an indirect method for controlling PD.

2.2.2 Soil subsurface detection

Soil subsurface detection techniques are increasingly used in agricultural applications. The sensing technologies with the ability to acquire subsurface measurements on-the-go and in a nondestructive manner are discussed. The technologies described under this category can be classified as contact or non-contact. For each technology the basic operational principles, technological advantages, and limitations are outlined. The nondestructive sensing
methods are based on changes in soil dielectric properties (soil dielectric constant, soil magnetic permeability, and soil electrical conductivity), discontinuities within the matrix as influenced by soil physical and chemical attributes (e.g. soil density, soil texture, strata, organic matter, soil temperature, soil salinity, and soil moisture). Nondestructive sensors consist of a transmitting and receiving antenna components. The material under test (MUT) can be placed between the transmitting and receiving antenna components, in a transmittance measurement mode, or the two components can coexist on the same facet of the MUT (soil), in a reflectance mode. In the reflectance mode, the principle of operation is to transmit and receive backscatter from the bulk soil matrix and target within the soil matrix. Figure 2.2, depicts a typical sensor with bistatic antennae with fixed common offset used to detect the seed on a closed trench nondestructively. Also, Figure 2.2 shows both the physical and electrical properties of soils and targets that are likely to influence nondestructive sensors. The discussed sensors should be capable of accurately detecting anomalies within the subsurface to determine the vertical distance relative to the topsoil surface.

Figure 2.2 The principle of operation for a nondestructive sensor for plant depth detection in a closed trench. Where, $T_x$ is the antenna transmitter, $R_x$ is the antenna receiver $\rho_i$ is the material density, $T_i$ is the material temperature, $\epsilon_i$ is the dielectric constant, $\mu_i$ is the magnetic permeability, $\sigma_i$ is the electrical conductivity.
2.2.2.1 Acoustic and ultrasound sensors

Acoustic Sensor (AS) technology employs sound waves to detect discontinuities within test material. A typical AS is composed of a transmitter and a receiver, which houses a piezoelectric material responsible for generating and receiving sound waves, at frequencies less than 20 kHz (infrasound) and greater than 20 kHz (ultrasound). Application of the electric field to the piezoelectric component produces mechanical strain on the piezoelectric material which then generates sound waves. These sound waves propagate into the soil and are reflected to the piezoelectric receiver as governed by material bulk density and dielectric properties. At higher material densities, sound wave reflections are significant. The reflected sound waves induce mechanical stress on the piezoelectric receiver which converts the waves into an electric field that is then recorded. The great advantage of using sound waves is that when propagating they do not undergo polarization or cannot be polarized (i.e., polarization is a phenomenon by which a vibrating wave is restricted to propagate in one direction). Sound waves are longitudinal because of the parallel relationship between sound wave oscillation and direction of waves through a medium e.g., air, soil (vibrating forward and backward). Other propagating modes include shear waves, surfaces waves and plate waves that can be used to characterize gases, solids, and liquid. In addition, the velocity of sound waves in solids is greater than in the air (330 $ms^{-1}$) by a magnitude of thousands. AS are highly sensitive, reliable, cost-effective, offer high resolution, stability, and are application specific (Hoummady et al., 1997; Vellekoop, 1998; Drafts, 2001). The AS is the preferred sensor technology in numerous fields, including physical (geological, spatial and structural evaluations), and biological (medical evaluations) sensing applications (Terzic, 2013). AS’s are used successfully to monitor structural health through nondestructive detection of structural defects or anomalies within the structural material well before the integrity of the structure weakens (e.g., aerospace structures). When an anomaly exists within a structure it creates a discontinuity in the structure that can be mapped (Finlayson et al., 2001). The principle of nondestructively detecting anomalies (property discontinu-
ity) within a bulk material may be extended to the agricultural seed depth detection.

AS sensors have been utilized in a number of forestry, food and agricultural applications. They have been used to detect features within a leaf to evaluate deficiencies and its maturity (Mikio et al., 2008). Grift et al. (2005) utilized ultrasonic sensors for detection of compaction zones or hardpan distributions in soils, based primarily on the effect of density changes on the measured acoustic responses. However, García-Ramos et al. (2005) stated, the main disadvantage of using ultrasound sensors to detect targets in soil may be that plant tissues greatly attenuates ultrasound waves.

Adamchuk et al. (2004) reported on the diverse applications of AS for agronomic research. For example, AS were used to map soil textures, soil compaction, soil bulk density, and hardpan detection. The ASs were used to determine soil layer interfaces, hence, providing soil depth profiling. However, the area of AS still remains under investigation to optimize their application in agricultural fields, as the actual relationship between the sensor output and physical state of the soil is not well understood. The application of AS has not been widely accepted, but with more research on the area, the technology will perhaps reach desired maturity and functionality. In the application of seed detection, AS sensor technologies may be applicable, since corn seeds have unique shapes and contrasting kernel densities, which could make seed depth profiling possible. When there is disparity between soils and corn kernel densities, mapping proximally buried seed depths may be possible.

2.2.2.2 Electromagnetic induction

EMI sensors are based on the fundamental principles of electromagnetics as described by Maxwell’s equations particularly Faraday’s law of electromagnetic induction (Annan, 2009; Sadiku, 2010). The alternating current through the transmitting coil leads to the formation of the pulsing or changing magnetic field. The changing magnetic field induces eddy current signals in the MUT, producing a secondary magnetic field, radiated to the soil surface to be captured by the receiving secondary coil (Won et al., 1998; Sudduth et al.,
The strength of these signals is measured at the secondary coil to establish the location and size of the target. Electromagnetic induction (EMI) sensors are used as a nondestructive technology for the detection of metallic and nonmetallic objects, unexploded ordnances, and buried landmines. When subsurface targets are metals (conductive i.e., stainless steel), then they can be successfully detected with high resolution, the location identified (distance), the shape, and the size established. Das et al. (1990) conducted an experiment to illustrate the effectiveness of the EMI technology to detect near ground surface metals. The experiment featured a vehicle-towed EMI sensor which provided locations of detected near ground surface metals. For a nonmetallic test material such as soils, EMI sensors respond primarily to the apparent electrical conductivity of the soil, which is a function of soil moisture, exchange capacity, particle charge, ionic molecules (e.g. sodium ions, chloride ions, and potassium ion), and clay content within the soil matrix (Doolittle and Brevik, 2014). Both, the soil bulk density and soil organic matter are highly correlated with soil electrical conductivity (Peplinski et al., 1995). Electrical conductivity can be used to assess soil quality (Williams and Hoey, 1987; Das et al., 1990; Sudduth et al., 2001; Corwin and Lesch, 2005). Hence, EMI sensors have been successfully used to quantify soil spatial variability, categorization of soils in agricultural fields, and mapping hydrologic unit boundaries (Adamchuk et al., 2015).

Hlaváčová and colleagues have exploited seed electrical (ionic) conductivity to evaluate seed aging, vigor and mechanical damage through their leachate. In the study, it was found out that there was significant correlation between ionic conductivity and mechanical damage of seeds, and ionic conductivity increased with temperature (Hlaváčová, 2003, 2009; Maryam and Oskouie, 2011). Also, dielectric properties of seeds can be argued to have significant importance other than just monitoring and sensing applications. Electromagnetic waves can be used for heating and drying of materials. The principle was determined to be beneficial in controlling insects that may otherwise cause damage to grains in storage facilities (Nelson, 2005). Applying the EMI technique to detect seed targets may be challenging in the sense
that agricultural seeds are dielectric materials with a low degree of ionic conductivity and have densities similar in magnitude as the soil matrix, depending on conditions. This could be viewed as a limitation for in-situ seed detection. However further research would be required to evaluate the technology for seed depth detection.

2.2.2.3 Magnetic sensors

Magnetic sensors measure the distribution of the magnetic flux strength established by the materials. The material should possess magnetic properties to be effectively detected by a magnetic sensor. An oscillatory propagating magnetic field wave magnetize the material, hence the MUT releases magnetic energy. The receiver then detects the released magnetic energy. The amount of the energy echoed back to the sensor signifies the magnitude of the magnetizing atom(s) in a material, and the location of anomaly can be identified, as well as the size of the anomaly. The magnetization process follows Faraday’s law of magnetic induction. Magnetic sensors can detect iron or nickel or cobalt in a bulk material. The most commonly used magnetic sensors for nondestructive evaluations are Nuclear Magnetic Resonance (NMR), Magnetic Resonance Imaging (MRI) and Magnetic Resonance Spectroscopy (MRS). The fundamental principles of operation of these sensors are based on materials nuclei (García-Ramos et al., 2005; Rossel et al., 2011). They exploit the magnetic properties of atomic nuclei of carbon ($^{13}$C is a stable isotope with six protons and seven electrons) and hydrogen ($^{1}$H - a stable isotope that has one proton) to map discontinuities. The $^{13}$C and $^{1}$H are capable of absorbing magnetic radiation at the frequency characteristic of the isotope.

The MRI is used largely in medical applications (biomedical imaging modality) for a full body scans by exploiting the microscale patterns of the magnetic field strength within cells and tissues (Davis et al., 2018). Recently, MRI has been employed in agriculture to measure soil water, scan potato defects, detect seeds in oranges and mandarins (Hernández-Sánchez et al., 2006). For the MRI, the water content (i.e. hydrogen atoms) is important
to provide sufficient pixel contrast within a body (Rosell and Sanz, 2012). Seed moisture content (hydrogen ions) may be sufficient to influence the magnetic properties within the seed structure, and MRI techniques may be feasible to detect buried seeds. However, the changes in magnetic properties of the surrounding soil matrix due to variations in soil moisture, age, and texture could overwhelm the magnetic signature of the seeds, which would adversely impact seed detection.

### 2.2.2.4 Radar technology

Radar is commonly used to detect a diverse range of subsurface objects. The waves have center bandwidth frequencies that range from 3 kHz to 300 GHz. The center frequency governs the sensor sensitivity, maximum penetration depth, sensor resolution, and the overall antenna size. For each center frequency extreme, there are advantages and disadvantages. High center frequency radar waves are more prone to high wave attenuation, and penetration depths are significantly reduced. However, at those high center frequencies, the best quantitative sensor resolution is attained, antennas are small, and portable. Conversely, at low center frequencies, greater depths can be assessed with lower resolution and attenuation. Figure 2.3, shows a detailed electromagnetic wave spectrum from the longest (low frequency) to the shortest (high frequency) wavelengths. Radio waves exploit the material electrical properties at various frequencies to detect discontinuities within the MUT. The exploited material electrical properties are the dielectric permittivity, magnetic permeability, and electrical conductivity. These three electrical properties affect wave propagation and define in greater detail the wave transmission through the MUT. Radar waves are extremely versatile, capable of detecting metallic and nonmetallic objects by employing their dielectric properties (Rossel et al., 2011; Novakova et al., 2013).
Additionally, the sensors have a robust built-in algorithm to scan and image subsurface targets, and at higher frequencies, small targets can be detected. The user must know the factors that can potentially influence the material electrical properties, and compromise radar performance. Radar devices can operate during the day, at night and over long ranges unmanned (Novakova et al., 2013).

Radar technology is affected by many factors such as the amount of water and ionic concentration in the soil medium. These factors increase the electrical conductivity of the soil which influences the radar wave attenuation. It is more desirable to have a conductive target than it is to have a conductive host (soil) medium. Also, the higher the soil bulk density and organic matter, the more the radar performance is adversely impacted. The radar technology provides a continuous sequence of reflected wave amplitudes from different material dielectric properties at interfacing boundaries. Therefore, an experienced and skilled operator is needed to interpret radargram results. Target size is critical when using radar technology. The smaller the target size, the more difficult it is to detect the target. Anomalies close to or surrounding the small target may shadow the real target preventing radar from picking the target.
**Ground penetrating radar**

Ground Penetrating Radar (GPR) technology is commonly used in noninvasive evaluations to detect subsurface objects, to assess road pavements, to assess rebar corrosion in bridges, and to evaluate structural faults. This technique is capable of providing planimetric position (x, y) and depth (z) of underground features using precise, high-resolution GPR antennas (Jol, 2009; Weia and Hashimb, 2012). GPR can detect metallic and non-metallic subsurface objects indiscriminately. The technique is based on the fundamentals of electromagnetics as expounded by James C. Maxwell. The GPR wave propagation, and the extent (depth) of subsurface penetration depends largely on the center frequency, and the dielectric properties of the MUT. There are three material dielectric properties exploited by GPR to map the subsurface: the dielectric permittivity, the magnetic permeability, and the electrical conductivity. These three dielectric properties constitute either a lossy or lossless media. In instances where material electrical conductivity is equivalent to zero, the material is referred to as lossless. In lossless media, such as air, wave attenuation is at its lowest or negligible level. Conversely, wave attenuation is highest in lossy (high electrical conductivity) materials. The utility of GPR has been proven in myriad applications to detect and locate pipes (e.g., polyvinyl chloride), cables, and conduits, road pavements and concrete inspection (e.g., locating reinforcing steel bars), forestry - detecting termite attack, and fungal decay in trees, and forensics and hydrogeological investigations - locating unmarked graves and water tables (Allred et al., 2004, 2005; Yelf, 2007; Eisenmann et al., 2012).

Researchers have been working extensively to improve on traditional methods of quantifying tree root biomass (which are extremely labor intensive, vastly destructive in nature, costly, provide limited quantification of root biomass and limited repeatability of measurements over time). The roots contribute a significant amount of soil carbon and organic matter, this information cannot be acutely predicted by excavation of the roots, but nondestructive GPR sensors have been successful. Butnor utilized GPR to study tree root biomass in Decatur County, Georgia, United States, to augment the conventional approaches.
research was focused on studying the distribution and quantification of root biomass in subsoils without digging roots out. GPR center frequencies ranging from 400MHz to 1.5GHz were selected and at these frequencies, the roots were resolved, and images of root biomass developed. The GPR investigation successfully predicted root size and depths, at which the roots resided beneath the surface (Butnor et al., 2001, 2003). In addition, related work on subsurface root distribution, root sizes, and roots depth were successfully predicted using the GPR with promising results (Barton and Montagu, 2004; Morelli et al., 2007; Bassuk et al., 2011).

Hirano et al. (2009) discussed factors that may be a significant hindrance on GPR performance when studying tree roots, with the main factor being the vulnerability of GPR waves to electromagnetic properties of the soil. Soils are inherently heterogeneous with unconsolidated mineralogy that make soil structures complex. The complexity gives the soil a depth variant media and therefore depth variant quantitative electrical properties (e.g., as influenced by soil moisture, and clay content), which can obstruct GPR performance. In the study, roots with different diameter sizes and volumetric moisture content were placed in the subsoil. Definitive mapping of roots with a large diameter and 80 percent volumetric water content was possible and easily detected. Conversely, roots with minimal diameter and 20 percent water were not easily detected by the GPR sensor. Tree root diameter and volumetric moisture content played a significant role in mapping the subsoil tree roots. Allred et al. (2008) used GPR to study subsurface root morphology. GPR technology was capable of detecting roots diameter as small as 2.5 mm at a frequency of 1.5GHz in sandy soils.

Research on using the GPR technique on agricultural application is expanding exponentially. The GPR has a broad impact pertaining to precision farming, as a nondestructive technology to distinguish buried features in agricultural soils (Adamchuk et al., 2004). In precision farming applications, it has been used to quantify soil moisture and salinity, evaluate and identify stratigraphy zones, locate water tables, and classify soils (e.g., arrangement of horizons, texture, soil density, and depth profiling of spatial variability). The GPR in-
struments are more efficient on detecting abrupt and dielectric discontinuities at interfacial boundaries making subsurface mapping and depth profiling relatively easy e.g., locating soil compaction or hardpan depths, soil moisture evaluations, mapping in-field or agricultural drainage pipes (Doolittle, 1987; Schellentrager et al., 1988; Raper et al., 1990; Odhiambo et al., 2002; Allred et al., 2004, 2005).

Seeds are similar dielectric materials to the 2.5 mm roots mentioned above. Therefore, it may be possible to detect seeds using GPR, provided seeds have sufficient water content to provide a difference in dielectric properties from the surrounding soil matrix. However, this may be a challenge since the water content of roots is significantly different from that of seeds and surrounding topsoil. Mapoka et al. (2016) modeled and evaluated the possibility of using a single point source GPR of 1.0 GHz frequency to detect buried corn seed targets. In the theoretical simulation study, it was observed that GPR model should be capable of detecting corn seeds embedded at a depth of 0.0762 m in a soil medium.

2.2.2.5 High energy ray sensing technologies

Gamma rays and X-rays

High frequencies and highly energetic electromagnetic radiations are the basis for gamma and X-rays, as seen from Figure 2.3. Gamma and X-rays involve highly energetic atoms such as neutrons and protons (Merzbacher and Lewis, 1958). These rays are highly dangerous, and precautions need to be taken to protect those who are running experiments as well as those who are near it. Radiation within this category is extremely energetic and can penetrate any absorbing material. However, depth of penetration is significantly attenuated by material thickness. In practice, lead materials can successfully attenuate gamma and X-ray radiation. A gamma spectrometer is used to measure gamma radiation from materials, and it can be performed by either active or passive sensors. Active gamma sensors generate and radiate photon energy whilst passive gamma sensors measure photon energy from naturally occurring radioactive isotopes. Viscarra Rossel et al. (2007) conducted a
study using a multivariate calibration for on-the-go proximal gamma ray spectrometry to measure soil properties. In the study, the calibration was executed by using a partial least square regression technique. Coarse sand and clay layers were effectively identified, and the chemical composition (i.e., pH profiles) was successfully predicted.

A typical X-ray machine is set to have the radiating source and the sensitive film detector on opposite sides, with an object placed in between. X-rays are propagated through an object or body, as they traverse through denser components of the body which absorb X-ray energy. Lightly dense portions of a body do not absorb as much X-rays as the denser portions. For example, in medical evaluation X-ray scans, bones are more visible while the flesh is not. In the same manner, airport security scanners use low-level frequency to provide a two-dimensional body image. Ambert-Sanchez et al. (2016) conducted a laboratory experiment to evaluate the soil macro-porosity and bulk soil density as influenced by tillage practices such as long-term chisel plough, and excessive and prolonged use of heavy equipment in the same area without till. In the study, a high resolution industrial-grade X-ray computed tomography (CT) and two conventional laboratory methods were used. The CT was found to be more useful and efficient in providing reliable qualitative and quantitative information pertaining to the soil structure, macro-porosity, and bulk density for different soil cores where different tillage methods have been practiced. Moreover, the CT proved to be efficient in detecting dry materials such as dry plant parts, fruits, and seeds, as well as fossilized materials (Rosell and Sanz, 2012). However, application of CT methodology on soils and assessments of fruits remains a specialized area in soil science research and food materials.

Researchers have reviewed different soil proximal sensing techniques which could measure spatial soil properties that could be useful for precision agriculture and general natural resource management. In the study, X-ray technique was found to be effective in providing information on specific locations (i.e., point data). Additionally, it was reported that the X-ray technique could assess and categorize soil horizons and describe soil morphology based on metal concentration in the soil. However, the study also found that X-ray and gamma ray
techniques have limited applications in soil science, primarily because these techniques are application-specific, their common use is in medical fields, and their usefulness in agriculture is limited (Adamchuk et al., 2015). The X-ray and gamma ray sensor are more suited to detect photon energy from radiating atoms. The agricultural seeds nuclei have not been scientifically proven to generate photon energy. Therefore, the application of these technique to detect buried seeds in the soil matrix maybe limited. Yet gamma and X-rays can be absorbed by high density materials or the disparity in material bulk density may enable detection.

2.3 Sensing Technology Classification

2.3.1 Subsurface detection

Table 2.1 presents the classification of sensing technologies discussed in this review. It provides a general breakdown of the sensing technology and type, operating frequency, process, cost, and operational protocol. All these sensors have been used in different studies for soil subsurface detection in agricultural applications. The safety feature in the table characterizes the sensing technology as safe or unsafe to the operator and is shielding necessary or not prior to usage.

2.3.2 Suitability of technologies to detect and range corn seeds

In this section, sensors are classified according to properties they use to detect targets or irregularities in a soil material or an object. Table 2.2 provides a summary of sensors based on the measured attribute for each sensor, the spatial sensor resolution, and sensitivity to the soil, and seeds. The sensors are either affected by one or more agronomic parameters to detect subsurface targets. Therefore, the measured attribute column shows the most important agronomic properties targeted by each sensor technology to produce a discernible output response (Adamchuk et al., 2004).
All the techniques presented in this review have applications to forestry and agricultural investigations, with some showing reasonable success. The nondestructive sensors were applied in a range of applications, and the successful application of each technique depends on a characteristic or measurand as shown in Table 2.2. Table 2.3 lists the specific application for each non-destructive sensor (Hoummady et al., 1997; Butnor et al., 2001, 2003; Allred et al., 2004, 2008; Yelf, 2007).

2.3.2.1 Detection

Each technique has a property that is quantifiable for the detection of target to be possible. The EMI and GPR techniques exploit soil and target dielectric properties such as dielectric permittivity, dielectric permeability, and electrical conductivity or the apparent electrical conductivity to locate subsurface targets. The EMI waves are sensitive to changes in soil apparent electrical conductivity which makes possible for the detection in earthen materials (Doolittle et al., 1994; Doolittle and Brevik, 2014). Agricultural seeds and soils are dielectric materials with inherently low electrical conductivity or ionic concentration. If seeds were to be buried in soils having higher moisture their apparent electrical conductivity would increase, therefore increasing the chance of detection by either the EMI and GPR. Corn seeds are not susceptible to the magnetic fields, because they are non-magnetic compounds. Since the seeds are non-magnetic, magnetic sensors which predominantly work on conductive materials (eddy currents for defect characterization) are not likely to successfly detect seed targets. MRI sensors are sensitive to water content due to the hydrogen ions, which makes MRI a possible technology for seed detection. In summary, the water content may be the most important factor in corn seed detection using MRI, EMI, and GPR sensors. An explanation of the constitutive properties (dielectric permittivity, dielectric permeability, and electrical conductivity) is provided below.

The dielectric permittivity is used to define and characterize the dielectric properties of materials. The dielectric permittivity is a complex function that is related to the electric...
energy storage and energy losses of a material, and the potential for polarization effect and can be expressed as shown in Equation 2.1;

\[ \epsilon = \epsilon' - j\epsilon'' \]  

(2.1)

where \( \epsilon \) is the effective dielectric permittivity, \( \epsilon' \) is the real dielectric permittivity and \( \epsilon'' \) is the dielectric permittivity energy loss factor. The absolute dielectric permittivity describes the behavior of the wave (electric field) as it interacts with the MUT. When a dielectric material is exposed to an electric field, energy can be stored through polarization effect (see Equation 2.2). The amount of energy stored implies wave propagation discontinuity as the wave phase and velocity are changing. The phenomenon occurs at the interfacial boundaries of varying dielectric permittivity within the MUT.

\[ D = \epsilon E \]  

(2.2)

where \( D \) is the dielectric displacement vector (\( Cm^{-2} \)), and \( E \) is the electric field intensity vector (\( Vm^{-1} \)). Equation 2.2 estimates polarization, and the complex absolute dielectric permittivity component \( \epsilon \) provides a phase difference between the electric field and the resulting polarization. The polarization phase difference \( (\delta) \) is calculated using Equation 2.3.

\[ \tan(\delta) = \left( \frac{\epsilon'}{\epsilon''} \right) \]  

(2.3)

In most cases, dielectric materials may have low electrical conductivity. In some soils, however, the electrical conductivity may be significant due to the ionic concentration and water molecules that transport positively charged ions. The conductive nature of a dielectric material such as soil enables the material to conduct an electric component hence inducing eddy currents within a soil. When a dielectric material conducts, it can essentially act as a media capable of transporting electric current when subjected to an electric field, as shown in Equation 2.4.
\[ J = \sigma E \] \hspace{1cm} (2.4)

\( J \) is the current density \((Am^{-2})\), and \( \sigma \) is the electrical conductivity \((S/m)\), which can be expressed as a complex function as shown in Equation 2.5

\[ \sigma = \sigma' - j\sigma'' \] \hspace{1cm} (2.5)

where \( \sigma \) is the effective electrical conductivity, \( \sigma' \) is the absolute electrical conductivity, and \( \sigma'' \) is the loss factor. To account for polarization losses at different center frequencies \((f)\) and losses due to the electrical conductivity \((loss\ factor)\) and also to cater for the dielectric polarization of a conductive material, the equation above can be expressed as shown in Equation 2.6

\[ \sigma = \sigma' + 2\pi f \epsilon_0 \epsilon'' \] \hspace{1cm} (2.6)

The center frequency governs the overall behavior and transmittance of waves through the MUT. According to Equation 2.6, at higher frequencies it is possible to increase MUT electrical conductivity. Therefore, the accessible penetration depth would be affected due to high attenuation, and sensor resolution of subsurface targets would be greatly decreased. A dielectric material with higher electrical conductivity may behave as a conductor when subjected to the electric field, whereby the current start to flow and zero net electric field within the MUT. The occurrence leads to a total reflection of the electric field, which may be a desirable event if corn seeds had the characteristic and undesirable event for the host material (soil). Thus, a factor that needs careful attention when a sensing mechanism is selected for a task. As such, the effect of the center frequency is very important in sensing mechanisms discussed in this review. The brief discussion of dielectric properties presented above describes the interaction behavior of the magnetic, and electric field (or EM fields) and dielectric materials (i.e., soils and seeds).
The dielectric properties of seeds are low at dry moisture content but increase as the moisture content changes. In addition, different seed coating to increase seed vigor and performance may impact seed dielectric properties, although the relative influence of the coatings has not been established. Agricultural seeds and soils have varying densities which can significantly affect sensor performance. Corn seeds have kernel density ranging from 1.27 to 1.38 $g cm^{-3}$ (Mészáros, 2007), and agricultural soils range in density from 1.2 to 1.6 $g cm^{-3}$ (Hillel, 2003). Due to the varying bulk densities between the soil and corn seeds, the use of acoustic and ultrasonic sensors, and X-ray/gamma sensor to detect buried corn seeds could be possible. However, the proximity in bulk densities may be challenging or introduce difficulties in detection.

2.3.2.2 Ranging

Accurate depth ranging depends on the measurement of the two-way travel time of the incident and reflective wave from the target, and a knowledge of the velocity of the wave through the material medium. A number of different techniques are used for estimation of the wave velocity, including the use of calibration targets at a known depth to determine wave velocity. In this case, the target depth is determined from the product of the estimated wave velocity and two-way travel time to the unknown target. However, if calibration targets of known depth cannot be used, the wave velocity can be estimated from theory based on the material permittivity. In cases where calibration targets of known depth cannot be utilized, and the spatial and / or temporal changes in permittivity of the material, algorithms for accurate prediction of soil permittivity are required, to estimate the wave velocity through the medium. Soil permittivity changes with soil moisture and texture, therefore, changes in soil permittivity must be accounted for to estimate target depth.

In this work, GPR depth estimation was performed by using the two-way travel time ($t$) and prediction of the soil dielectric permittivity ($\epsilon$). The two-way travel time was carefully analyzed and extracted from the GPR data. The time represents the delay or the wave
travel time from the GPR transmitter to the target and back to the receiver. The $\epsilon$ is used to correct for the GPR wave velocity ($v$), shown in Equation 2.7, based on the velocity of light in a vacuum ($c$) (Wang et al., 2016). The $\epsilon$ parameter can be computed using the Topp’s dielectric equation and soil mixing models (Topp et al., 1980; Peplinski et al., 1995). These models are fairly accurate and have reasonable fidelity in predicting $\epsilon$. From these identified parameters, depth ($d$) can be resolved following the Equation 2.8 (Wang et al., 2016).

\[
v = \left( \frac{c}{\sqrt{\epsilon}} \right)
\]

\[
d = \left( \frac{vt}{2} \right)
\]

Acoustic, ultrasound, EMI, GPR, X-Ray and Gamma ray sensors all apply the same basic principles in ranging applications. In nondestructive testing using these techniques, the material under test (MUT), is normally considered uniform, with the exception of defects or anomalies within the MUT. Therefore, the distance between the probe and the discontinuity (inhomogeneity) within the MUT can be estimated using the position locating law (Krautkrämer and Krautkrämer, 2013), shown in Equation 2.8. In soil sensing applications, an additional challenge is that the MUT is known to be non-uniform and therefore the wave velocity varies depending on conditions.

2.4 Nondestructive Sensor Application For SD-KI for Agricultural Development

**SD-KI: Seed Detection and Knowledge Integration**

Control of the down-force or margin load measurements and on-the-go soil moisture measurements are procedures currently used to adjust PD to improve and optimize corn production. To date, corn seed PD prescription maps are unavailable for use, because of a
lack of sensor technologies to map seed depth. Accurate prediction of planting depths using sensor technologies based on known soil conditions and downforces for an area of the field could help develop prescription seeding maps. This has the potential to provide closed loop-control of seed planting depth based on field prescription maps, and monitoring actual seed depth during planting operations to develop actual planting depth maps. The sensor based closed loop control of active pressure control systems could facilitate accurate site-specific seed planting depth for varying soil and operational conditions.

This review has reviewed acoustic, ultrasound, EMI, radar, magnetic, MRI, X-ray, and gamma ray sensors, as possible nondestructive sensing technologies to detect and quantify seed PD. Amongst the nondestructive sensors discussed herein, the most promising techniques, would appear to be GPR. The GPR can detect subsurface target and provide target depth profile. The only negative aspect is their relative cost. The sensors may be used to obtain accurate PD measurements to help establish better planting protocols that ensure seeds are placed at the correct and consistent depths. This could facilitate the development of easy-to-use and low cost sensors, and control systems for large-scale deployment. Thus, large-scale field prescription maps can be developed and used for managerial systems, for the application of variable planting across a field. Development of accurate tools to document planting depth would enhance research on developing accurate and smart planters, and optimization of planting depth management strategies to improve crop production.

2.5 Conclusion

Several types of nondestructive sensor technologies for development of in-field seed depth measurement have been discussed and compared in this review. Each sensor technology has specific benefits and limitations for soil subsurface detection. The reviewed sensors in this publication could potentially lead to the development of precise, affordable, and robust systems capable of measuring the seed planting depth. This would enable the accurate control and monitoring of planting depth for sustainable and economic corn production.
using commercial active planter pressure control systems. Based on the classification system included in the review of sensor geophysics and material (soil and seed) properties during planting, GPR was identified as a suitable candidate for detecting seed and quantifying seed depth and with the possibility to integrate it for on-the-go planting performance analytics. Future studies will be required to validate the best technology pathways and perform rigorous validation and verification for field readiness.

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Nielsen, R. (2001). Stand establishment variability in corn. Report, from Agronomy Department, Purdue University, West Lafayette, IN, 47907-1150.


Table 2.1 Classification of sensor based on their sensing type, operating frequency, operation, cost, process, and safety

<table>
<thead>
<tr>
<th>Sensing technology</th>
<th>Sensing type</th>
<th>Operating frequency</th>
<th>Process</th>
<th>Cost</th>
<th>Operation</th>
<th>Safety</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic sensor</td>
<td>ND</td>
<td>20 Hz-20 kHz</td>
<td>stationary</td>
<td>inexpensive</td>
<td>active</td>
<td>✓</td>
</tr>
<tr>
<td>Ultrasonic sensor</td>
<td>ND</td>
<td>&gt;20 kHz</td>
<td>mobile/</td>
<td>inexpensive</td>
<td>active</td>
<td>✓</td>
</tr>
<tr>
<td>EMI</td>
<td>ND</td>
<td>$10^6$-$10^9$ Hz</td>
<td>mobile/</td>
<td>inexpensive/</td>
<td>active</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>stationary</td>
<td>expensive</td>
<td></td>
<td></td>
</tr>
<tr>
<td>GPR</td>
<td>ND</td>
<td>$10^6$-$10^9$ Hz</td>
<td>mobile/</td>
<td>expensive</td>
<td>active</td>
<td>✓</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>stationary</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Magnetic sensor</td>
<td>ND</td>
<td>-</td>
<td>stationary</td>
<td>inexpensive</td>
<td>active</td>
<td>✓</td>
</tr>
<tr>
<td>MRI</td>
<td>ND</td>
<td>-</td>
<td>stationary</td>
<td>expensive</td>
<td>active</td>
<td>×</td>
</tr>
<tr>
<td>X-rays</td>
<td>ND</td>
<td>$10^{17}$-$10^{20}$ Hz</td>
<td>mobile/</td>
<td>expensive</td>
<td>active/  passive</td>
<td>×</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>ND</td>
<td>$10^{20}$-$10^{24}$ Hz</td>
<td>mobile/</td>
<td>expensive</td>
<td>active/ passive</td>
<td>×</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>stationary</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ND - Nondestructive. The ✓ indicates safe to use while the × not safe or may require shielding for operator safety.
Table 2.2  Suitability and Comparative study of requirements for detection of Seeds

<table>
<thead>
<tr>
<th>Sensing technology</th>
<th>Measured attribute</th>
<th>Spatial resolution</th>
<th>Sensitivity to material</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Soil</td>
<td>Seed</td>
</tr>
<tr>
<td>Acoustic sensor</td>
<td>Acoustic impedance (soil texture and compaction or bulk density, depth variability)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Ultrasoni sensor</td>
<td>Acoustic impedance (soil texture and compaction or bulk density.</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>EMI</td>
<td>Soil electrical conductivity (soil moisture content and salinity, and CEC)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>GPR</td>
<td>Dielectric properties, i.e., dielectric permittivity, electrical conductivity (soil texture and moisture content and salinity and organic matter, and CEC)</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Magnetic sensor</td>
<td>Iron or nickel</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>MRI</td>
<td>Water content, and carbon content</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>X-rays</td>
<td>Electrons or Photons, and density</td>
<td>✓</td>
<td>✓</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>Photons and density</td>
<td>✓</td>
<td>✓</td>
</tr>
</tbody>
</table>

Iron, nickel and cobalt have saturation magnetization, $\sigma_i$, at room temperature. The check ✓ indicates the likelihood of obtaining a response from both the soil and seed (suitability fit), and the × indicates the unlikely chance or uncertainty of getting a response.
Table 2.3  Specific applications for each non-destructive technique discussed in this review

<table>
<thead>
<tr>
<th>Sensing technology</th>
<th>Measured attribute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic and ultrasound sensors</td>
<td>Agriculture - locating hardpans and soil texture mapping; Geotechnical investigations - soil sampling, profiling stratigraphy, identifying hard grounds and compaction zones, can be used in all soil types; Physical and chemical sensing - temperature, pressure, density, mass loading, and conductivity; Medical.</td>
</tr>
<tr>
<td>EMI</td>
<td>Military - landmines and unexploded ordanances; Locating metals.</td>
</tr>
<tr>
<td>GPR</td>
<td>Construction - detecting and locating pipes (e.g., polyvinyl chloride), cables, conduits, other subsurface or buried objects; Agriculture - measuring soil moisture, mapping dielectric targets, mapping rocks, and soils (clay), and agricultural drainage pipes; Transport - Road pavements and concrete inspection (e.g., locating reinforcing steel bars); Forestry - Detecting termite attack in trees and fungal decay in trees, and locating tree roots; Forensics and hydrogeological investigations - locating unmarked graves and water tables.</td>
</tr>
<tr>
<td>Magnetic sensor</td>
<td>Concealed metals.</td>
</tr>
<tr>
<td>MRI</td>
<td>Medical; Agriculture - scan potato defects, detect seeds in oranges and mandarins.</td>
</tr>
<tr>
<td>X-rays</td>
<td>Proximal soil sensing - surface and subsurface soil properties</td>
</tr>
<tr>
<td>Gamma rays</td>
<td>Radio-isotope detectors measure density and water content.</td>
</tr>
</tbody>
</table>
CHAPTER 3. USING GPRMAX TO MODEL A GROUND PENETRATING RADAR (GPR) TO LOCATE AGRICULTURAL CORN SEED AS AN ATTEMPT TO MEASURE PLANTING DEPTH

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Abstract

Technological techniques to measure planting depth (PD) nondestructively have not been developed. A 2D gprMax simulation study was conducted to investigate the effects of soil electromagnetic properties on Ground Penetrating Radar (GPR) waves. The primary objective was to examine the possibility of using the GPR as a nondestructive sensor to detect subsurface corn seeds with a goal of measuring PD. A conventionally fixed offset gprMax antenna in contact with the soil surface was used in the simulations. Two corn seed models of different materials and sizes were simulated having properties of natural and
synthetic (metal) corn seeds. The seed models were spherical having diameters of 0.006 m and 0.024 m to simulate small and large corn seeds. Corn seed models were embedded in three homogeneous soil models (sandy-loam, loam, clay-rich), and 1.6 and 2.6 GHz antenna models were used as excitation frequencies. A-scans and B-scans were obtained from the simulations. The A-scans showed that all targets (small natural corn and metal corn models; sizeable natural corn and metal corn models) successfully provided response amplitudes proportional to their dielectric properties in sandy-loam and loam, but not in clay-rich. In high bulk density soils GPR waves failed to penetrate the soil models and neither target was detected. As to antenna responses, the 2.6 GHz antenna provided better response amplitudes to both targets. In the driest soil models (2.5%, and 5%) no response amplitude signatures were observed. Also, in dry and relatively dry soil models (15%), the simulation times were much shorter to obtain a response amplitude from targets (with feeble response amplitudes) compared to relatively wetter soils. In order to validate our models, laboratory experiments with three treatment factors (soil type, planting depth, and moisture contents) were conducted. Results indicated that in dry soils corn seeds could be detected using a 2.6 GHz GPR antenna; however, the detection varied substantially within replicates of the same moisture group. Future research is necessary to understand the effects of soil moisture in the detection variability of buried corn seeds.

Keywords GprMax, Electromagnetic waves, Finite Difference Time Domain, Dielectric Permittivity, Corn Seed, GPR

3.1 Introduction

Remarkable research has been devoted towards developing techniques that can improve and control downforce pressure on planter press wheels, as a strategy for maintaining a consistent planting depth (PD) over a given field topography, and control compaction by the planter depth control wheels. The control systems include hydraulic, mechanical, and pneumatic based actuator systems. In many cases, the technologies, however, fall short of the desired outcome, leading to uneven seedling emergence because of inconsistent planting depths, due to incorrect setting of target downforce
pressure for the conditions. Several studies have shown the consequences of incorrect planting depths and the subsequent effect on germination and final yield (Hussen et al., 2013; Becks-Hybrids, 2014; Doerge et al., 2015). Due to the importance of PD on final yield, the technologies to measure in-field planting depth during planting operations could have significant economic benefits. This study, evaluates the potential to use ground penetrating radar (GPR) as a nondestructive technique to measure seed PD in a closed trench.

GPR is a nondestructive geophysical technique that operates by transmitting and receiving electromagnetic waves from features within a test material. It exploits test material dielectric properties to map discontinuities and can furnish depth profiles of features in the test material. Also, GPR can provide high-resolution imagery of subsurface features as governed by the antenna center frequency and test material dielectric contrast. GPR technology has been applied broadly in agriculture; it has been used successfully to classify soil horizons, locate buried roots and agricultural drainage pipes (Yoder et al., 2001; Odhiambo et al., 2002; Allred et al., 2004, 2005).

3.1.1 Soil mixing model

Soils are inherently complex and the effect of several soil physical properties on GPR performance must be considered. GPR sensors respond to changes in dielectric properties. Soil physical properties that have the potential to influence soil dielectric properties are soil bulk density, soil composition (sand, silt, and clay), soil moisture content, and soil particle density. Thus, soil mixing models have been developed to predict the influence of soil physical properties on soil dielectric properties (Peplinski et al., 1995). A soil mixing model is a semi-empirical dielectric model that estimates the real and imaginary components of the dielectric permittivity (dispersive material properties) for the soils. Soil mixing models have been used to relate soil physical properties and soil composition with bulk soil dielectric permittivity and soil electrical conductivity (Miller et al., 2004; Quan et al., 2014). A realistic soil model can be modeled based on the stochastic distributions of the soil properties. Some authors referred to the models as pedo-transfer functions in which soil dielectric properties are functions of the natural soil composition structure (Hendrickx et al., 2003).
3.1.2 GPR operation principles

The typical GPR system consists of a transmitter and receiver antenna, either individual antennas separated by some distance or a combined transmitter / receiver antenna. The GPR transmits electromagnetic waves at center frequencies that can range from $\sim 100$ Hz up to 2.6 GHz into the soil. The antennas are located above the soil surface at a height predetermined by the operator. The operating center frequency in most cases is associated with the application and desired resolution. Electromagnetic waves are transmitted into the test material, and dependent upon the material’s dielectric properties, some fraction of the energy is reflected while the remaining energy is transmitted through the material or absorbed in the material. Additionally, the center frequency and test material dielectric properties can lead to polarization of the material which can affect wave propagation (Neal, 2004; Sadiku, 2010). A commonly-used GPR system is a common-offset bistatic GPR antenna placed proximal to the soil surface, transmitting waves into the soil and receiving reflected waves from both the air-soil and soil-seed interfaces as governed by dielectric properties of each material (Fig. 3.1). In GPR terminology, a plot of the reflected wave amplitude as a function of time is called a trace or A-scan. The A-scan represents a single static response from a target (Fig. 3.4). Moving a GPR antenna along a flat soil surface while collecting and recording data at different spatial positions result in the creation of a B-scan image. The B-scan is made up of a series of A-scans merged for a given spatial distance, therefore, represented as a 2D image with the time of flight on the y-axis and spatial distance on the x-axis.

3.1.3 Electromagnetic theory

Electromagnetic (EM) theory involves the study of moving EM fields in a given space and time. EM theory is governed by James Clerk Maxwell’s equations and constitutive laws (Jol, 2009; Sadiku, 2010). Constitutive laws define materials properties which govern the behavior of EM signals through a test material. The constitutive laws employ three material dielectric properties which are the electrical conductivity ($\sigma$), dielectric permittivity ($\epsilon$) and magnetic permeability ($\mu$). These dielectric properties describe materials’ relationship with the EM fields (Norimoto, 1976; Odhiambo et al., 2002; Orfanidis, 2002; Neal, 2004; Annan, 2009; Jol, 2009; Sadiku, 2010). In this study, the soil dielectric properties were estimated using soil mixing models, and the subsequent effect on EM wave propagation behavior was modeled. EM wave technology has been used in numerous agricultural...
Figure 3.1  GPR operational principles showing antenna separation, air, transmitted, refracted, reflected waves from air-soil and soil-seed interfaces (Sato, 2009)

sensing applications (Topp et al., 1980; Brisco et al., 1992; Yoder et al., 2001; Odhiambo et al., 2002; Allred et al., 2004, 2005, 2008). However, in this paper the possibility of locating agricultural corn seed depth using EM waves was examined, which has not been previously investigated.

3.1.4  gprMax modeling

An open-source GPR modeling software package called gprMax (GNU General Public License v3) was developed to simulate GPR wave propagation for diverse applications, by simulating responses from different material and size targets (Warren et al., 2016). This software solves Maxwell’s equation in 2-D or 3-D by employing the Finite Difference and Time Domain (FDTD) numerical method. The FDTD is a numerical analysis established to model computational electrodynamics (Yee, 1966) by solving partial differential equations to find the estimate of the spatial description of the fields. Moreover, FDTD discretizes Maxwell’s functions in space and time by utilizing the central differences
method. Two parameters, cell size ($\Delta x, \Delta y, \Delta z$) and time step ($\Delta t$) are used to discretize the domain with specific spatial and temporal resolutions and affect FDTD accuracy. The cell size needs to be smaller than the smallest wavelength of the wave. In modeling GPR wave propagation, the cell size has to be at least a tenth less than the propagating electromagnetic wavelength, i.e. $\Delta x = \frac{\lambda}{10}$, to minimize numerical errors within an orthogonal grid. This criterion was used for selecting the most effective cell size and time step. The time step must be less than the ratio between the cell size and the speed of light, $c$ ($\text{m s}^{-1}$) to satisfy the Courant limit condition that relates the stability of the spatial discretization to the required time step. The discretized components follow the Yee Cell lattice, where constitutive properties for a particular medium were defined per cell joint of the Yee Cell (Kunz and Luebbers, 1993; Ketata et al., 2010; Schneider, 2010; Warnick, 2011).

The FDTD framework uses the Yee scheme, where the two complementary meshes of the electric and magnetic field components are solved alternately. Yee (1966) termed the principle “leapfrog”, where the electric component at a time, $t$, is used to calculate the magnetic component at a time, $t + 0.5\Delta t$, and in turn, the electric component computed at the time, $t + \Delta t$. The sequential update of the two components continues until the simulation time (time-window) defined elapses. The absorbing boundary conditions were defined to truncate an infinite simulation domain to a finite size. Moreover, the fields reaching the edge of the media were truncated and absorbed preventing reflections into the computational domain; hence, at the boundaries, all components are zero. Moreover, the Gaussian waveform signal source was defined and injected into the gprMax model to initiate wave propagation (Warren et al., 2016).

This study investigated the possible use of GPR for detecting corn seed in a closed furrow with different soil conditions. The objectives of this research were to:

1. model GPR transmission through a lossy media,
2. evaluate the probability of success detecting corn seed in closed soil furrows using GPR under different soil conditions, and
3. investigate the effect of corn seed material and size on the corn seed response.
3.2 Methodology

3.2.1 Seed model properties

In the simulation model, two materials of different sizes were modeled to represent corn seeds. First, the physical and dielectric properties of *Zea mays* (corn) seeds were used. Second, a synthetic seed was modeled using the conductance of metal for its properties. These two seed models helped develop an understanding of the effects of seed material and size on the energy reflected from the seeds. Corn seeds have distinct shapes that can be modeled using conical, rectangular, triangular or even spherical shape-forms (Fig. 3.2a). In the model, a spherical shape was used because it represented corn seeds well and was easy to implement in the model. A procedure similar to Mousaviraad et al. (2017); Mousaviraad and Tekeste (2018) was adopted to estimate corn kernel 2D axial dimensions. Measurements to estimate kernel size were taken from a sample of 50 kernels. A digital caliper with a 0.01 mm resolution was used to acquire these measurements (Fig. 3.2b). The rectangular length, width, and thickness measurements of each corn kernel were measured and averaged to estimate the mean kernel size and rectangular volume of the sample of corn harvested in 2016 (20% M.C., Iowa State University farm, Boone County, Iowa). The equivalent spherical volume, and corresponding spherical radius was determined to be 0.006 m. Thus, a spherical corn seed model was implemented with a 0.006 m radius and classified as a small size kernel. To evaluate the effect of kernel size, a large spherical corn kernel model was developed with radius four times that of the small kernel model or 0.024 m.

The research done by Nelson (1987, 2005); Trabelsi and Stuart (2003) predicting the dielectric permittivity of bulk corn samples enabled estimation of the dielectric permittivity for a single corn kernel. The bulk dielectric permittivity of the corn kernel is a function of bulk density, single kernel density, moisture content, temperature, and frequency. The bulk density of corn is 0.7208 g cm$^{-3}$ (56 lb. bu$^{-1}$) and for a single corn kernel, the density ranges from 1.27 to 1.38 g cm$^{-3}$ (Mészáros, 2007). The optimum moisture content for corn seeds, stored at a room temperature of 12.78°C, to ensure the highest possible percentage germination rate is 11% moisture content (Sayre, 1940). Therefore, the dielectric permittivity of a single kernel seed was calculated according to the models developed by Nelson and Datta (2001); Nelson (2015), for corn seeds with 11% moisture content, 1.275 g cm$^{-3}$ kernel density, and 0.7208 g cm$^{-3}$ corn bulk density. The relative dielectric permittivity ($\epsilon_r$) of a single corn seed was estimated to be 3.90 (unitless), and the magnetic permeability ($\mu$)
for dielectric or food materials is usually equal to the permeability of free space \( \mu_0 = 4\pi \times 10^{-7} \text{ H m}^{-1} \) (Datta, 2001). Therefore, the seed relative magnetic permeability (\( \mu_r \)) was set to 1 (unitless). Agricultural corn seeds in storage have low moisture levels; therefore, they have extremely low ionic movement which leads to low ionic conductivity for corn seeds. However, based on Datta (2001), the electrical conductivity (\( \sigma \)) of a dielectric or food material is directly related to the dielectric permittivity and frequency, \( f \) (Hz), given as, \( \sigma = \omega \epsilon, \text{ S m}^{-1} \), \( (\omega = 2\pi f \) is the angular frequency, rad s\(^{-1} \), and \( \epsilon \) is the dielectric permittivity, F m\(^{-1} \)). Metals (e.g. stainless steel) are highly conductive or are perfect electric conductor (PEC). PEC is a built-in material function defined in gprMax (Warren et al., 2016). Based on table of electrical conductivity for metals stainless steel corn seed was defined to have electrical conductivity of \( \sigma = 1.45 \times 10^6 \text{ S m}^{-1} \) (CSNDT, 2013). The electrical conductivity of metal overshadows the dielectric permittivity polarization effect in a metal; therefore, the stainless steel relative dielectric permittivity and permeability were defined as \( \epsilon = -1 \) (unitless), \( \mu = 1 \) (unitless) (Howlader and Sattar, 2015).

Figure 3.2  (a) Images of corn shapes, including; circular/roundish/sphere shapes (i, ii, vi), and triangular/conical shapes (iii, iv, v) and measurement of the corn physical parameter using a digital caliper
3.2.2 Soil model properties

Soil heterogeneity is known to adversely affect GPR performance by decreasing signal to noise ratio due to dielectric discontinuities in the soil which leads to additional reflections or random scattering back to the soil surface consequently masking the intended target responses. For instance, Chaudhari (2015), found that the amount of organic matter content in the soil has a substantial impact on dielectric properties. An increase in the soil organic matter content increased both the soil dielectric permittivity and loss factor. Also, soil surface roughness as a result of soil irregularities (rocks, soil texture, aggregates) may have an impact on incidental wave and polarization which may affect wave penetration direction (Flores et al., 2009). For instance, in rough surfaces, it is possible to have step changes in dielectric properties of heterogeneous soils, which can influence GPR wave propagation. In general, waves are more diffusive in rough surfaces and more directional in flat surfaces, and rough soil surfaces may lead to total absorption of the transmitted wave by the dielectric medium, a phenomenon referred to as Brewster Angle or polarization angle (Hajnsek and Papathanassiou, 2005). Therefore, in the proposed lossy soil model, the soil surface was considered to be flat, and other interferences that could otherwise cause unwarranted backscatter, such as grass and wood materials (organic matter) were not included to reduce model complexity. In the developed model, soils were assumed to be homogeneous, time-invariant, and isotropic. The homogeneity assumptions of the model make the soil model linear, providing explicit and easy understanding of numerical results as influenced by critical soil and target factors that could limit in situ GPR wave survey (Twizere, 2011). However, these model assumptions suppress in situ soil conditions that are likely to degrade GPR waves during actual GPR measurements to locate corn seeds. In the study, three soil textures: sandy-loam, loam, and clay soils were investigated. Three soil physical properties, volumetric moisture content (VMC), soil composition (sand, silt and clay content), and soil bulk density, were investigated. Soil mixing models were used to predict soil dielectric permittivity and soil electrical conductivity. Soil compositions for the three soil textures in Table 3.1 were based on the Soil Survey Laboratory Information Manual (Burt, 2011).
Typically, the field soil VMC at planting is between 15% to 40% (Weiler et al., 1998). According to Weiler et al. (1998) 15% is the minimum soil moisture required at planting (Note: this minimum moisture content may vary from soil type to soil type). Therefore, in our simulation, two VMCs (2.5%, 5% VMC) below the minimum required soil moisture, and three VMCs (15%, low 25%, 40%, high) within the acceptable soil moisture range, were investigated. Some moisture contents do not reflect moisture contents during ploughing season (i.e., 2.5 to 5%) but crucial for GPR model evaluation.

In addition, three soil bulk densities are assessed: two normal (acceptable) soil bulk densities at planting were used to compute soil dielectric properties: 1.42 g cm$^{-3}$ for sandy-loam soil texture, 1.20 g cm$^{-3}$ for loam and 1.20 g cm$^{-3}$ to 1.29 g cm$^{-3}$ clay soil textures (Hillel, 2003). A third soil bulk density of 3.00 g cm$^{-3}$ (the density was crucial for GPR model evaluation) was selected for all soil textures, to investigate the impact of high soil bulk density on GPR wave propagation. The selection of the bulk density was based on the soil bulk density of < 1.60 g cm$^{-3}$ required at planting. A soil particle density of 2.66 g cm$^{-3}$ was used for all simulation (Hendrickx et al., 2003; Miller et al., 2004). Since soils are inherently heterogeneous, it was challenging to understand the individual effect of different soil parameters, i.e., VMC, bulk density, and soil composition on sensor response at a time. In the simulation, three soil models; sandy-loam, loam, and clay were used with different soil conditions. For each soil texture, one soil property was varied at a time while others were kept constant. With this approach, a range of soil dielectric properties were determined as functions of the different soil properties (Tables 3.2 & 3.3), to investigate the effect of the individual soil properties.

### Table 3.1 Soil Composition values to Determine Soil Dielectric Properties

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Soil composition</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>%Sand</td>
</tr>
<tr>
<td>Sandy loam</td>
<td>60</td>
</tr>
<tr>
<td>Loam</td>
<td>48</td>
</tr>
<tr>
<td>Clay</td>
<td>20</td>
</tr>
</tbody>
</table>
Table 3.2  Estimating soil dielectric permittivity and soil electrical conductivity simulation parameters of sandy loam, loam, and clay at different soil bulk densities and five soil VMC

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Sandy loam</th>
<th>Loam</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ϵ</td>
<td>σ</td>
<td>ϵ</td>
</tr>
<tr>
<td>2.50</td>
<td>3.41</td>
<td>0.04</td>
<td>2.89</td>
</tr>
<tr>
<td>5.00</td>
<td>4.25</td>
<td>0.04</td>
<td>3.55</td>
</tr>
<tr>
<td>15.00</td>
<td>8.30</td>
<td>0.04</td>
<td>6.96</td>
</tr>
<tr>
<td>25.00</td>
<td>13.59</td>
<td>0.04</td>
<td>11.60</td>
</tr>
<tr>
<td>40.00</td>
<td>23.84</td>
<td>0.04</td>
<td>21.04</td>
</tr>
</tbody>
</table>

Sandy loam at 1.42 g cm$^{-3}$, Loam at 1.20 g cm$^{-3}$, and Clay at 1.20 g cm$^{-3}$

Table 3.3  Dielectric permittivity and soil electrical conductivity simulation parameters of sandy loam, loam, and clay estimated at five VMC and soil bulk density greater than maximum possible density.

<table>
<thead>
<tr>
<th>Soil texture</th>
<th>Sandy loam</th>
<th>Loam</th>
<th>Clay</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ϵ</td>
<td>σ</td>
<td>ϵ</td>
</tr>
<tr>
<td>2.50</td>
<td>6.58</td>
<td>3.14</td>
<td>6.31</td>
</tr>
<tr>
<td>5.00</td>
<td>7.76</td>
<td>3.14</td>
<td>7.31</td>
</tr>
<tr>
<td>15.00</td>
<td>13.29</td>
<td>3.14</td>
<td>12.32</td>
</tr>
<tr>
<td>25.00</td>
<td>19.98</td>
<td>3.14</td>
<td>18.53</td>
</tr>
<tr>
<td>40.00</td>
<td>32.35</td>
<td>3.14</td>
<td>30.37</td>
</tr>
</tbody>
</table>

Fresh water has high relative dielectric permittivity (~81) which influenced the effective soil dielectric permittivity. Soil electrical conductivity was largely governed by the soil texture, and soil bulk density (Table 3.2 & 3.3). When the soil bulk density was increased to greater than maximum possible, each soil texture had an increased soil electrical conductivity. These soil electrical properties were used in the gprMax to evaluate GPR’s capability to detect different target materials and sizes.

3.2.3 Model of a seed in the soil

A 2D simulation model consisting of a homogeneous distribution of relevant soil properties and seed dielectric properties was developed and used as the input to the gprMax software. The 2D model was used to investigate the likelihood of obtaining a response from buried seeds that would result in seed detection. The corn seed targets were modeled to be at a 0.07 m depth in the soil media. The 2D model specified the rectangular domain of 0.24 m, 0.21 m, and 0.002 m (x, y, z; 2D models in gprMax are a single cell slice of a 3D model), whereby the soil model coordinates within
the rectangular domain were at 0 m, 0 m, 0 m (bottom corner) and 0.24 m, 0.17 m, 0.002 m (top corner) creating a space for the antenna above the soil (Fig. 3.3 a & b). The geometric model shown in Figure 3.3(b) was stored as an *vti* object file, and a paraview package (*paraview package is a visualization tool used to display gprMax simulation vti format images displayed in Fig. 3.3b*) was used to display the geometry. The wave was discretized in space and time with cell size of $\Delta x = \Delta y = \Delta z = 0.002$ m and a time step of $\Delta t = 4.717$ picoseconds. These cell sizes were maintained throughout the simulation.

![Diagram](image)

(a) A 2D model of an embedded seed 0.07 m deep in the soil with pulsing antenna source placed directly on top of the soil surface. A small section was extracted and enlarged to show cell size and dielectric properties that define each cell. (b) GprMax geometrical model of an embedded spherical seed 0.07 m in a soil media.

A lossy soil media was defined by the dielectric permittivity, the dielectric magnetic permeability, and soil electrical conductivity as described in the soil model properties section. The simulation time window was specified to be 5 nanoseconds. The algorithm was designed to have perfectly matched layer (PML) absorbing boundaries conditions (ABC) which enclosed the entire simulation domain at the edges and the purpose of ABC is stated in the gprMax modeling subsection of this paper and further information on ABC is presented (Mur, 1981, 1998; Schneider, 2010).
A Gaussian pulse waveform was provided as the excitation source in the gprMax model. The Gaussian waveform source had a current source of 1 Amp (with a pulse time of $5.3125 \times 10^{-8}$ seconds and pulse width is the ratio of 0.5 to the simulation frequency) of which the polarization was specified to be on the z-direction. The specified current was converted internally by the gprMax software to the electric field strength V m$^{-1}$ amplitude (herein referred to as the response amplitude); therefore, based on the simulation model dielectric properties the response amplitudes were simulated (Tables 3.4 to 3.6). The simulations were conducted at two frequencies: 1.6 and 2.6 GHz. A common fixed offset antenna was used in simulations, whereby the antenna was positioned directly on top of the soil surface and stepped at increments of 0.002 m across the x-direction (horizontal) distance of the domain to locate the buried seed target. Every time the antenna was moved a new A-scan (trace or line scan) was recorded; therefore, sixty traces were specified to create the B-scan. The total horizontal distance covered by the transmitter and receiver as they were moved over the corn seed model was 0.12 m. The A-scan results were exported to Matlab for visualization.

3.3 Simulation Results and Discussion

In the GPR A-scans, the responses due to the reflections at the air-soil and soil-seed interfaces can both be observed (Fig. 3.4). The response amplitudes for both materials was reasonable and as expected. However, for the 2.5% and 5%, VMCs were not included in the plot as they registered very low response amplitude (unsubstantial dielectric permittivity). The second reflections from the bottom of the large sphere (0.024 m) were observed (Fig. 3.4b). The small natural corn seed did not have observable second reflections (Fig. 3.4a). The electric field interaction with large seeds (4 time actual size) provided higher peak response amplitudes compared to small seeds. The GPR wave response to the small sphere approximates the Raleigh scattering as the natural corn seed model was small in comparison to the dominant pulse wavelength.
All figures display a clear soil reflection (Fig. 3.4). The magnitude of the transmitted signal into the soil decreases proportionally according to the magnitude of the soil dielectric permittivity and soil electrical conductivity. The dielectric contrast magnitude governs wave reflections both at the air-soil and soil-seed boundary; hence, the response amplitudes displayed in Figure 3.4a & 3.4b indicate the magnitude of dielectric contrast between mediums in the model. For relatively dry soils, the reflections at the air-soil interfaces were observed to be lower, and transmitted energy into the soil was higher compared to wet soils.

In contrast, at higher soil volumetric moisture contents (VMC) (25%, 40%) the soils absorbed significant proportions of the GPR wave that was transmitted into the soil, and more of the wave was reflected at the air-soil interface. In drier soils (15% and below), the simulation time was much shorter (computation was shorter to compute a model solution) to record the response amplitude from corn seeds compared to relatively wetter soils. Higher VMC contributed to higher dielectric contrast, between the natural corn seed and the soil models, hence the relatively higher response amplitudes in lossy wet soils, Figure 3.4. The phenomenon, however, was observed to be opposite for metal seed models, where the response amplitudes decreased with increase in VMC, Table 3.4 & 3.5.

As expected, the response amplitudes on wetter soils were observed to exhibit a longer time of flight (Fig. 3.4), which meant that the GPR wave velocity slows down in high soil VMCs. The phenomenon was observed for both natural and synthetic corn seed models. Throughout the simulation, the soil bulk density was kept constant for sandy loam, loam and clay soils, respectively.

The response amplitudes were extracted from the A-scans and recorded to indicate the presence of corn seed models. The response amplitude magnitude was observed to be proportional to the dielectric properties causing the change at the soil-seed interface, the GPR wave frequency, the size and material of the corn seed model. The time of flight was influenced by the soil conditions which governed the transmission of waves through soil model. The response amplitude and time of flight for all the corn seed models are shown in Tables 3.4 to 3.6.

The synthetic metal seeds were subjected to the same soil simulation parameters in Table 3.2 & 3.3. The synthetic metal seeds were distinguishable by response amplitude associated to size. The sizeable synthetic metal seed had higher response amplitudes compared to the smaller counterpart (Table 3.4 & 3.5). The time of flight trends were observed to be like that of natural corn seeds when soil VMC was high. Large seeds provided the large surface area with which the GPR wave could
interact. Regardless of size, synthetic metal corn seeds were highly responsive to GPR waves, both in the dry and wet sand and loam soil conditions, respectively. At the driest soil conditions (i.e., 2.5%), the response amplitudes for either metal seed size were large. Unlike the natural corn seeds, synthetic metal seeds did not have strong second reflection; because metals are highly conductive, the electric field reaching the conductive seed gets neutralized leading to a zero net electric field within the conductor. Thus, the entire portion of the GPR wave was reflected. Moreover, as the GPR wave traversed through the wet soils, it was subjected to higher impedance resulting from VMC and to some degree from soil composition.

The high clay content soil yielded rather high soil electrical conductivity which created high impedance and attenuation for the GPR wave propagation. In the simulation, a small proportion of the transmitted wave penetrated the soil surface and instantly decayed to zero, therefore failing to reach neither corn seed target. No response amplitude was registered from the embedded seed models in higher clay content. A higher portion of the GPR wave was reflected at soil boundary interface. The model indicated that clay-rich soils might present challenges that would make mapping seeds a problematic undertaking using GPR. Neither target in clay-rich soil provided any response amplitude signature.

Figure 3.4  A-scans to evaluate GPR waves through sandy-loam soil at different volumetric moisture content (VMC) with natural corn seed model of (a) small radius 0.006 m, and (b) large radius of 0.024 m.
Table 3.4 Simulation obtained from different VMC, and a soil bulk density of 1.42 g cm$^{-3}$ in sandy loam soil using an antenna frequency of 1.6 GHz.

<table>
<thead>
<tr>
<th>VMC(%)</th>
<th>Small natural corn seed model</th>
<th>Large natural corn seed model</th>
<th>VMC(%)</th>
<th>Small SM corn seed model</th>
<th>Large SM corn seed model</th>
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</thead>
<tbody>
<tr>
<td></td>
<td>TWTT(ns) Peak Amp.(Vm$^{-1}$)</td>
<td>TWTT(ns) Peak Amp.(Vm$^{-1}$)</td>
<td></td>
<td>TWTT(ns) Peak Amp.(Vm$^{-1}$)</td>
<td>TWTT(ns) Peak Amp.(Vm$^{-1}$)</td>
</tr>
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<td>2.50</td>
<td>2.00 16</td>
<td>1.61 36</td>
<td>2.50</td>
<td>1.47 318</td>
<td>1.46 408</td>
</tr>
<tr>
<td>5.00</td>
<td>2.02 21</td>
<td>1.80 38</td>
<td>5.00</td>
<td>1.57 309</td>
<td>1.56 406</td>
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<tr>
<td>15.00</td>
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<td>2.15 80</td>
<td>15.00</td>
<td>1.97 292</td>
<td>1.96 425</td>
</tr>
<tr>
<td>25.00</td>
<td>2.50 64</td>
<td>2.54 119</td>
<td>25.00</td>
<td>2.36 278</td>
<td>2.35 430</td>
</tr>
<tr>
<td>40.00</td>
<td>3.00 74</td>
<td>3.04 167</td>
<td>40.00</td>
<td>2.94 156</td>
<td>2.93 415</td>
</tr>
</tbody>
</table>

TWTT - Time-way travel time in nanoseconds, Peak Amp. - Peak Amplitude from seed models and SM - Synthetic metal

### 3.3.1 Soil bulk density and frequency

The effects of higher soil bulk density and antenna frequency were evaluated. The soil bulk density adversely impacted GPR wave propagation by increasing both soil dielectric permittivity and soil electrical conductivity. These two parameters contributed to high soil impedance, creating an impenetrable and highly attenuating soil surface. Just like clay-rich soil, soil bulk density confounds GPR sensing applications. High density completely impeded GPR waves from entering the soils, subsequently making them unable to detect the target. Thus, no seed target response was observable in high soil bulk density soils. Also, given the same higher soil bulk density at a higher frequency of 2.6 GHz, shallowly embedded seed models could not be mapped due to high attenuation or absorption of the signal at a high frequency.

Consequently, there were no obvious target responses in both higher clay content and soil bulk density at frequency $\leq$ 2.6 GHz. However, when high frequency was used with sandy-loam soil with low soil bulk density of 1.42 g cm$^{-3}$, all targets (small natural corn and metal corn; sizeable natural corn, and metal corn) could be observed with larger response amplitudes. Table 3.6 presents responses from the small and large natural corn seed models in sandy loam.
Table 3.5  Simulation obtained from different VMC, and a soil bulk density of 1.2 g cm$^{-3}$ in loam soil using an antenna frequency of 1.6 GHz

<table>
<thead>
<tr>
<th>VMC(%)</th>
<th>Small natural corn seed model</th>
<th>Large natural corn seed model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TWTT(ns) Peak Amp.(Vm$^{-1}$)</td>
<td>TWTT(ns) Peak Amp.(Vm$^{-1}$)</td>
</tr>
<tr>
<td>2.50</td>
<td>1.71 39</td>
<td>1.67 32</td>
</tr>
<tr>
<td>5.00</td>
<td>1.80 44</td>
<td>1.70 28</td>
</tr>
<tr>
<td>15.00</td>
<td>1.98 46</td>
<td>2.03 63</td>
</tr>
<tr>
<td>25.00</td>
<td>2.36 55</td>
<td>2.41 98</td>
</tr>
<tr>
<td>40.00</td>
<td>2.95 68</td>
<td>2.99 154</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>VMC(%)</th>
<th>Small SM corn seed model</th>
<th>Large SM corn seed model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TWTT(ns) Peak Amp.(Vm$^{-1}$)</td>
<td>TWTT(ns) Peak Amp.(Vm$^{-1}$)</td>
</tr>
<tr>
<td>2.50</td>
<td>1.41 271</td>
<td>1.39 359</td>
</tr>
<tr>
<td>5.00</td>
<td>1.50 267</td>
<td>1.48 363</td>
</tr>
<tr>
<td>15.00</td>
<td>1.85 257</td>
<td>1.84 383</td>
</tr>
<tr>
<td>25.00</td>
<td>2.24 252</td>
<td>2.21 396</td>
</tr>
<tr>
<td>40.00</td>
<td>2.85 241</td>
<td>2.80 297</td>
</tr>
</tbody>
</table>

Table 3.6  The effect of simulation frequency on obtaining a response amplitude from natural corn seed model at different soil VMC, and a soil bulk density of 1.42 g cm$^{-3}$ in sandy loam soil using an antenna frequency of 2.6 GHz

<table>
<thead>
<tr>
<th>VMC(%)</th>
<th>Small natural corn seed model</th>
<th>Large natural corn seed model</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>TOF(ns) Peak Amp.(Vm$^{-1}$)</td>
<td>TOF(ns) Peak Amp.(Vm$^{-1}$)</td>
</tr>
<tr>
<td>2.50</td>
<td>1.34 24</td>
<td>1.35 35</td>
</tr>
<tr>
<td>5.00</td>
<td>1.37 28</td>
<td>1.37 28</td>
</tr>
<tr>
<td>15.00</td>
<td>1.86 65</td>
<td>1.88 97</td>
</tr>
<tr>
<td>25.00</td>
<td>2.27 86</td>
<td>2.28 169</td>
</tr>
<tr>
<td>40.00</td>
<td>2.88 94</td>
<td>2.90 242</td>
</tr>
</tbody>
</table>

A high center frequency leads to shorter wavelengths and increased resolution which improved the response amplitudes of small and shallow embedded corn seed model targets in sandy loam and loam soils. For instance, at a low center frequency (1.6 GHz), the responses for small natural corn seed models (radius 0.006) were low (Fig. 3.4 & Table 3.4). However, given similar sandy loam soil conditions at a high center frequency (2.6 GHz), the response amplitudes increased by approximately 25% compared to the response amplitudes in Table 3.4 (small natural corn seed model). For the large natural corn seed models, the increment was approximately 30%. That held true for all targets under investigation, in which the higher frequencies provided larger response amplitudes from either target size.
This simulation study evaluated the soil conditions and targets that would lead to conditions that were unfavorable for successful GPR detection responses and identify soil conditions in which seeds could be found in the soil after planting with GPR. For instance, clay-rich and denser soils need to be avoided since the attenuation was rapid under those conditions. Conversely, a high center frequency would be beneficial as high frequencies provide larger response amplitudes than low center frequencies.

The B-scans (Fig. 3.5 to 3.8) illustrates the dielectric contrast between the soil and the seed. The stronger the blue color on the B-scan represents higher negative response amplitude and the converse for the brighter reddish color. The implication here is that a dielectric material (soil and seed) would have a blue color response first, followed by red and then blue as seen in the figures below and vice versa for synthetic corn models. For example, referring to the bigger natural corn seed model (0.024 m; Fig. 3.6), the first blue color response can be seen at top and second reflection also blue response at bottom with red in between. These color contrasts becomes more apparent as the dielectric corn seed model size was larger and with increase in VMC.

Figure 3.5 Natural corn seed model response of radius 0.006 m in sandy loam at 15% VMC and soil bulk density (BD) of 1.42 g cm\(^{-3}\) (a) B-scan at a center frequency of 1.6 GHz, and (b) B-scan at a center frequency of 2.6 GHz
Figure 3.6 Natural corn seed model response of radius 0.024 m in sandy loam at 15% VMC and soil BD of 1.42 g cm$^{-3}$ (a) B-scan at a center frequency of 1.6 GHz, and (b) B-scan at a center frequency of 2.6 GHz.

Figure 3.7 Synthetic metal corn seed of radius 0.006 m on sandy loam at 15% VMC and soil BD of 1.42 g cm$^{-3}$ (a) B-scan at a center frequency of 1.6 GHz, and (b) B-scan at a center frequency of 2.6 GHz.
In practice, the response amplitude magnitude depends on the contrast between electrical properties of the target/anomaly and surrounding matrix, to detect the presence of an anomaly or a target. The simulation model results indicate that there is some likelihood that natural corn seeds could be detected by GPR waves, under certain conditions.

3.4 Simulation Model Verification

The gprMax simulation model in this study corresponds with most of the work that has been performed regarding detecting dielectric and conductive targets. Twizere (2011), has shown that an increase in soil clay content led to an increase in dielectric properties particularly the effective dielectric constant of the soil model. According to his model evaluation, the wave velocity decreased rapidly due to high dielectric constant, absorption and the reflection of the waves increased at high soil density. Thus, a limited amount of GPR waves can penetrate the surface, with higher time delays and rapid attenuation. The phenomenon corresponds to the findings of this paper, where no corn seed target response amplitudes were observed at higher clay content both at lower and higher VMC. Moreover, Miller et al. (2002) has shown in his GPR modeling work, that moist soils and clay soils greatly attenuate GPR waves. In this simulation study, it was evident that the GPR waves entering the soil surface decreases proportionally to increase in VMC. The simulation results indicated that as VMC increases from 15% to 40%, corn seed models evidently provided better...
response amplitudes which coincided with a study performed by Miller et al. (2002). Their results on detecting nonmetallic landmines of dielectric constants of 3.2 were more accessible at higher moisture rather than at lower moisture. At lower VMC, there was not enough contrast between the soil and nonmetallic landmine to provide a substantial response, similar to our study. The synthetic metal corn seed models were highly responsive to GPR waves in all soil conditions. However, at higher VMC, the response amplitudes tended to decrease. This was associated with attenuation masking the wave reflection.

GPR waves have been primarily considered by researchers in agriculture as a goal to improve quality data collection for precision agriculture such as measuring moisture locating drainage pipes and hardpans and studying roots morphology and biomass. In the investigation of tree roots biomass, at higher clay and VMC attenuation was rapid and the assessed depth was severely restricted (Butnor et al., 2001). Butnor et al. (2001) used two antenna center frequencies of 400 MHz and 1.5 GHz in their investigation. The 1.5 GHz antenna provided significant resolution, and a more significant number of buried roots were distinguished in the upper soil profile compared to the 400 MHz antenna. In our simulation model, at higher antenna center frequency of 2.6 GHz, the dielectric corn seed provided higher response amplitude compared to 1.6 GHz antenna. In addition, Butnor et al. (2001) demonstrated that root sizes had a profound impact on the response amplitude. The bigger the target, the higher the response amplitude. They indicated that the moisture content in roots had great impact on the detectability of the roots.

The gprMax simulation results were aligned with results reported by Butnor et al. (2001). A positive implication for GPR detection of in-situ corn seeds, is that seeds are live grains and have a certain percentage of moisture content in them. In our simulation, the corn seed dielectric constant was estimated using a corn seed moisture content of 11%. The estimated dielectric constant created a substantial dielectric contrast between the seed model and the surrounding soil model which led to proportional GPR wave response amplitudes presented in this paper. For natural corn model the dielectric contrast resulted in increasing response amplitudes that were proportional with the increase in soil VMC for the different soil types.
3.5 Experimental Verification

The simulation results indicate that corn seeds can be detected in certain soil conditions with strong response amplitudes (Tables 3.4 to 3.6) or hyperbolic responses (Fig. 3.5 to 3.8), based on simulation, we opted to use soils with low electrical conductivity (nonsaline), clay content, and densities for possible mapping of corn seeds. In sandy-loam soil using a 2.6 GHz antenna, it was observed that the response amplitudes (shown in Table 3.6) were much improved compared to the 1.6 GHz antenna results (shown in Table 3.4). Since soil models were assumed to be homogeneous, the real soils were processed (crushed and sieved to remove clods and other sediments) and prepared accordingly. Laboratory experiments under controlled environmental conditions were performed in soil bins using a 2.6 GHz GPR antenna. The nonsaline sandy-loam of 67% sand, 25% silt, and 8% clay, with a measured density of 1.41 g cm$^{-3}$ was used in the validation process.

Three soil moisture contents classified as dry (averaged 3.0%), low (averaged 11.3%), and medium (averaged 16.7%) were assessed. The measured VMCs of 3.0%, 11.3%, and 16.7% corresponded to the simulation VMCs of 2.5%, to approximately 15.0%. The Pioneer P0339AMXT variety of Precision Design Round size with a measured moisture content of 10.1% (proximal to 11% corn moisture used in simulation). At low soil, VMC of 11.3% and field corn moisture of 10.1% creates almost an environment where the GPR might not detect the corn because of similar values of moisture. The corn variety was buried at three depths, (0.0381m, 0.0635m, and 0.0889m) and at two different seed spacing (0.1524 m, 0.254 m). Five replicates were collected per soil moisture. Data were processed using the matGPR package to enhance readability and interpretation. The acquired data contained horizontal bands or ringing-noise, reverberations from the antenna, and clutter. The first processing step was filtering the horizontal bands to suppress their effect. However, in some cases filtering suppressed pixels with important target information, making detection of the target more difficult. A Fast Discrete Curvelet Transform (FDCT) was then used to clarify edges within the image and followed by an edge detection algorithm to enhance them. However, the algorithm parameters used in the filtering depended on each GPR image.
3.5.1 Experimental results and discussion

The collected GPR data from the experimental design were met with mixed success. Therefore, the selected B-scans are presented in Figure 3.9 & 3.10. The figures show (a) the raw B-scan with partial detection of corn seeds and (b) the processed B-scan with more enhanced edges and reduced clutter or noise.

![GPR data collected from dry sandy-loam soil](image)

**Figure 3.9** GPR data collected from dry sandy-loam soil (a) GPR raw data and (b) Processed GPR data. Key: red arrows mark nominal corn seed positions, yellow arrows show a response which could be thought to be from the corn seed or clutter, and white arrow shows the approximate corn response. $t_1, t_2$, and $t_3$ represents the time of flight to the corn seeds which also corresponds to the nominal depth.

B-scan in Figure 3.9 was collected in dry sandy-loam with Pioneer P0339AMXT PDR variety. It was observed in the data that not all the buried corn seeds were detected. Those that were buried shallow had the highest probability to be detected. The deeper the corn seeds were, the harder they were to detect. Moreover, in some of the replicated B-scans, no traceable responses were visible either in a raw or processed GPR image. In general, drier soils present greater probability that the corn seeds could be detected. Even though soils were dry, it is evident from Figure 3.9a that responses from seeds were evanescent (quickly fading) as the GPR wave was traversing deeper and targets exhibited faint hyperbolic responses. However, in our simulation results, no response amplitude was registered in dry soils. The GPR waves are sensitive to moisture, the sandy loam soil, and field corn had an average of 2.95%, and 10% moisture contents, respectively. The moisture difference (7.1%) between the two may have contributed to the detection ability of corn seeds in the laboratory tests, which was not likely according to the simulation results. In the simulation, the dielectric contrast
between the soil model (\(\epsilon = 3.41\) or \(4.25\), at 2.5\%, or 5\% VMC) and corn model (\(\epsilon = 3.9\), at 11\% moisture) was approximately 0.35 or 0.49 which does not make a strong dielectric contrast.

The simulation model results indicate that in medium moisture conditions corn seeds should successfully be detected due to the higher dielectric contrast. However, in the experimental results, the dielectric contrast between the surrounding soil and the corn seeds was observed (Fig. 3.10a). If there was any dielectric contrast between the two, it probably could have been masked by other factors within the surrounding soil matrix, such as the attenuation of waves and slow traversing wave velocity due to higher moisture, and irregular reflection patterns due to clutter. The processed B-scan, Figure 3.10b, show multiple hyperbolic responses within the B-scans which suggest that corn seed response could be among the several responses seen on the figure. Therefore, based on our reference B-scan and processed B-scan we marked the region where the corn seeds could have resided. Multiple reflections where the corn seeds were thought to be, made it difficult to discern which response is from the corn seed. This phenomenon was observed across the replicates collected at low and medium soil VMC.

![GPR data collected from moist sandy-loam soil](image)

**Figure 3.10** GPR data collected from moist sandy-loam soil (a) GPR raw data and (b) Processed GPR data. Key: red arrows mark corn seed positions.

The extracted TWTT and response amplitude from the dry, low, and medium VMC groups are presented in Table 3.7. The TWTT and the response amplitudes were extracted from processed B-scan (Fig. 3.9b and 3.10b) using the FORTRAN algorithm. In the algorithm, the apex of the hyperbolic response is identified in the B-scan by specifying a window which then the algorithm resolves the two parameters automatically. Features were defined in dry soils (less interference)
which made it easier to specify a window to extract the information compared to wetter soils due to the high level of clutter noise. The extracted TWTT were adjusted to remove the coupling time at the soil-air interface (time zero-correction). Moreover, the TWTT can be used to estimate nominal corn seed depths. It was evident from Table 3.7 that at dry VMC the response amplitudes are higher compared to the low and medium VMC group.

Table 3.7 Experimental results obtained from different VMC, and a soil bulk density of 1.41 g cm$^{-3}$ in sandy loam soil using an antenna frequency of 2.6 GHz and field corn variety: P0339AMXT PDR size.

<table>
<thead>
<tr>
<th>VMC(%)</th>
<th>Peak Amp.(Vm$^{-1}$)</th>
<th>Time points, $t_i$</th>
<th>TWTT (ns)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.0</td>
<td>1076</td>
<td>$t_1$</td>
<td>0.92</td>
</tr>
<tr>
<td>2.9</td>
<td>1064</td>
<td>$t_2$</td>
<td>0.68</td>
</tr>
<tr>
<td>2.3</td>
<td>1815</td>
<td>$t_3$</td>
<td>0.54</td>
</tr>
<tr>
<td>10.9</td>
<td>1198</td>
<td>$t_1$</td>
<td>1.43</td>
</tr>
<tr>
<td>10.5</td>
<td>619</td>
<td>$t_2$</td>
<td>1.08</td>
</tr>
<tr>
<td>11.3</td>
<td>814</td>
<td>$t_3$</td>
<td>0.75</td>
</tr>
<tr>
<td>15.8</td>
<td>248</td>
<td>$t_1$</td>
<td>1.62</td>
</tr>
<tr>
<td>15.0</td>
<td>397</td>
<td>$t_2$</td>
<td>1.12</td>
</tr>
<tr>
<td>17.1</td>
<td>602</td>
<td>$t_3$</td>
<td>0.87</td>
</tr>
</tbody>
</table>

An opposite trend of the peak response amplitude was observed between the simulation (Table 3.6) and experimental results (Table 3.7). The time of flight showed to be following the same trend as those from the simulation. At low VMC, the detection was quicker and conversely, at higher VMC, the detection time was slower.

3.6 Conclusion

Utilizing ground penetrating radar (GPR), for seed depth detection is highly dependent on the soil physical properties and contrast between the dielectric properties of the seed and surrounding soil matrix. The gprMax 2D simulation models were developed for preliminary evaluation of the potential to use GPR for seed depth detection. Laboratory experiments were conducted in an attempt to validate the trends exhibited in the simulation model results. The overall conclusions from this research study include:
• The simulation results predicted that GPR waves could be used to successfully locate natural corn seed models in certain field conditions with low clay content and low soil bulk density. There was substantial attenuation in clay-rich soils and high soil bulk density soils, which made successful seed detection unlikely.

• A higher frequency (2.6 Ghz) was determined to have a better probability of the detection of small (standard size) corn seeds.

• The simulation results predicted that response amplitudes were better at 40%, 25%, and 15%, respectively and very low to negligible detection at 5%, and 2.5% soil volumetric moisture contents. The dielectric contrast between the seed and soil model was necessary for the detection.

• Laboratory experiments showed that in dry soil conditions the 2.6 GHz could detect shallowly buried corn seeds; however, as corn seed depth increases, GPR wave strength rapidly decayed leading to no detection.

• In laboratory tests, corn seed detection became increasingly difficult at higher soil moisture contents. This was not consistent with the simulation results. In simulation results higher moisture created higher dielectric contrast between the soil and natural corn seed model. While in actual soils the dielectric contrast was masked by myriad soil inclusions. Higher soil moisture led to high attenuation and also at higher moisture contents, and other soil inclusions and clutter due to constructive and destructive interference between multiple overlapping hyperbolic responses resulted in greater loss of B-Scans quality.

• The results obtained from the simulation model aligned with work performed by several researchers in locating buried metal and dielectric (roots) targets in different soil conditions.

• The simulation and experimental results indicated that the GPR reflections have the potential to locate corn seeds in sandy loam, loam, and low clay content soils (unless the soil bulk density is high) at certain soil moisture contents. The overall conclusion was that detecting buried corn seeds in soils may be possible using the GPR, but requires additional studies to determine if robust and reliable detection of buried corn seeds is possible under all necessary field conditions.
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CHAPTER 4. EXPERIMENTAL APPROACH TO QUANTIFYING CORN SEED SIMULANT MEASUREMENT ERROR USING A GROUND PENETRATING RADAR

A paper modified from a manuscript submitted in the Journal of Precision Agriculture

Kenneth O.M. Mapoka$^{a,*}$, Stuart J. Birrell$^a$, David J. Eisenmann$^a$, Mehari Tekeste$^a$, and Huaiqing Wu$^b$

Abstract

Planter manufacturers’ provide open-loop pressure-based active control systems to improve planting depth (PD) control. These systems could be significantly enhanced using real-time seed depth sensors for closed-loop pressure-based control accuracy with respect to PD. The primary objective of this proof of concept study was to use ground penetrating radar (GPR) and evaluate its effectiveness in detection in sandy-loam and loam soils. GPR limiting factors for detecting shallowly buried targets include the target material, shape, and size. Synthetic Corn Seeds (SCS) were used to simulate the agricultural corn seeds with a uniform flat profile shape of three different sizes (small, medium, and large). SCS were made of stainless steel and wood and facilitated an understanding between the SCS and typical farm soil dielectric properties. Antennas operating at 1.6 and 2.6 GHz were used in a laboratory to measure the suitability of the GPR to distinguish SCS from soils. The antennas were subjected to several treatment factors: soil moisture contents, soil types, salinity, seed materials, and seed sizes. The detection rate varied with soil salinity, type and moisture contents. Highest SCS detection rate (up to 100%) was at the lowest salinity and moisture contents. Estimation of PD was performed using the two-way travel time (ns), and the dielectric permittivity (predicted from Topp’s dielectric, soil mixing, and constant dielectric). The statistical regression analysis showed that the Topp’s dielectric model was a useful empirical model to estimate the dielectric permittivity used for calculating PD. The Topp’s dielectric model had Mallows Cp $\leq 3.94$ and $p = 4.00$ for wood seeds measurement error predictions. The GPR measurement error
was 7.86% which corresponded to a coefficient of planting depth accuracy value of ±0.005 m relative to the theoretical depth. Under certain workable soil conditions, SCS signatures were of high quality and conversely, in other soil conditions target signatures were sub-par or nonexistent. The interaction between higher soil volumetric moisture content and salinity were detrimental to GPR waves. The implication was the utility of GPR for SCS detection was site-specific, and a detailed understanding of the soil matrix is necessary for successful SCS detection. The SCS material and size had a profound effect on the GPR attainment of readable radargrams.

**Keywords** coefficient of planting depth accuracy, Dielectric permittivity, Ground Penetrating Radar, Volumetric moisture content, planting depth

**Acknowledgements** The authors thank the Center for Nondestructive Evaluation (CNDE) GPR laboratory at the Iowa State University for providing the GSSI instrument. Moreover, extended gratitude to Mr. Ethan Thies, Mr. Colton Finley, and Mr. Zachary Buscher for their valuable assistance in collecting soils from the farm.

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### 4.1 Introduction

Planter manufacturers’ provide open-loop pressure-based active control systems to improve planting depth (PD) control. These systems could be significantly enhanced using real-time seed depth sensors for closed-loop pressure-based control accuracy with respect to PD. Determining the PD is an essential procedure to ensure that corn seeds are planted at the optimum depth and for accurate closed-loop PD control. Research is needed to measure PD in farm soils, however, no substantial efforts have been demonstrated or presented in the literature to take advantage of the advent technological tools to measure PD. A laboratory study was conducted at Iowa State University to detect and estimate the PD error using a noninvasive ground penetrating radar (GPR).
In this study, two portable-GPR of 1.6 and 2.6 GHz antenna center frequencies were used to detect the contrast between buried corn seeds in sandy-loam and loam soils.

The contrast between agricultural Corn Seeds (CS), soil physical properties, and GPR waves have not yet been documented. However, recent research by Mapoka et al. (2016) has been conducted to help understand the dielectric properties of buried corn seeds in different soils. From the model-based results, it was understood that in certain soil conditions the GPR was not viable to map CS. Moreover, GPR limiting factors in the detection of shallowly buried targets include the target material, shape, and size. The stated challenges are the fundamentals exploited by GPR for subsurface detection. Therefore, detecting shallow buried agricultural CS and estimating their depths may be a challenging and possibly a difficult task to execute using the agricultural CS without first using the synthetic targets as a benchmark for the overall investigation. In lieu of that, in this research, the proposal was to use the Synthetic Corn Seeds (SCS) to create an understanding of the relationship between the physical properties of the SCS, the soils, and the effect of the target material, and size in the detection. The SCS were used to simulate the agricultural CS with a uniform flat profile shape with different sizes that resembled the small, medium, and large CS. The experimental test runs were set under controlled laboratory conditions.

Further, in-situ PD measurements of agricultural CS may be more challenging. Alternatively, the experimental trials could also be performed in-situ using the SCS. The planting spacing and depth of the SCS can be calibrated to resemble the typical spacing and depth used on a typical planting process. Therefore, the two agronomic variables can be measured in-situ using the GPR. The spacing would be a variable used for identification of seed locations within the furrow. Based on the spacing and depth tolerances (accounting for variability), the in-situ PD error may be determined. The results from this proof of concept study may help with the actual detection of CS in future research.

Since the PD is rarely measured, the seeding accuracy may be left to speculation or the intuition of an operator. Therefore, in this paper, the Coefficient of Planting Depth Accuracy (CPDA) was briefly introduced. The CPDA parameter would be an added evaluation component for the performance of the GPR in detecting and accurately quantifying the SCS PD.

The objective of this proof of concept research was to use and evaluate the GPR antennas to detect buried SCS at constant PD in sandy-loam and loam soils at different conditions. The specific objectives were to:
• evaluate the effect of soil salinity, VMC, and texture on the estimation of PD error of SCS,

• select an effective method to predict the minimal percent PD error for further implementation of the statistical analysis to develop a suitable model for the GPR to detect agricultural corn seeds; hence, computing the CPDA.

4.2 Material and Procedures

4.2.1 Synthetic corn seeds (SCS)

In subsurface detection, the shallow buried target material, shape, and size may be limiting factors for the GPR. Hence the effectiveness and accuracy of the GPR for the detection and estimation of the corn seed PD was assessed by utilizing Synthetic Corn Seeds (SCS). Agricultural corn seeds have different shapes (i.e., rectangular, conical, and spherical). Therefore for SCS used in this study, assumed a flat profile shape based on a flat corn seed. For the evaluation of material and size effect on the detection, the SCS were made of two materials, metal (stainless steel of 5 mm thickness) and wood (plywood of 5 mm thickness). The measurement dimensions of agricultural CS were determined from a sample size of 30 CS, using a digital caliper of accuracy 0.01 mm. Accordingly, an average was calculated \((L \times W \times D) 0.0124 \times 0.0080 \times 0.0050 \text{ m}\) to represent a normal corn dimensions (small size). Since the size of shallow buried SCS would play significant role in the detection using GPR, the small size dimensions were doubled (medium) and quadrupled (large), accordingly. However, the D parameter of the SCS was not varied across the two materials. These three sizes for the metal and two sizes for the wood material were cut and used in the experimentation. The smallest wooden seeds were not cut and were therefore excluded in this study. Two synthetic wooden corn seed sizes: medium and large were evaluated. The study equivalent to using small synthetic wood seeds was deferred for future research where agricultural corn seeds would be used. Stainless steel is an electrically conductive material with an electrical conductivity of \(1.45 \times 10^6 \text{ S/m}\) (CSNDT, 2013). The poplar plywood is a dielectric material with permittivity values ranging from 6 to 8 depending on the moisture content and with low ionic electrical conductivity and density. The synthetic plywood seeds were the closest physical presence to resemble the agricultural corn seeds; therefore, the idea was, the usage of plywood would closely help with understanding the relationship between the soil matrix, agricultural corn seeds, and the
GPR electromagnetic waves. Table 4.1 provides a justification on the selection of synthetic corn seeds for proof of concept (Mészáros, 2007).

Table 4.1 Comparison summary of real corn and synthetic corn seed properties

<table>
<thead>
<tr>
<th>Seed type</th>
<th>Moisture (%)</th>
<th>BD</th>
<th>$\epsilon$</th>
<th>$\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real corn</td>
<td>11 to 14</td>
<td>1.27 to 1.38</td>
<td>3.9 to 5.0</td>
<td>-</td>
</tr>
<tr>
<td>Synthetic wood</td>
<td>Variable range</td>
<td>0.7 to 1.00</td>
<td>6 to 8</td>
<td>-</td>
</tr>
<tr>
<td>Synthetic metal</td>
<td>-</td>
<td>7.7</td>
<td>1</td>
<td>$1.45 \times 10^6$</td>
</tr>
</tbody>
</table>

BD - Bulk density (g cm$^{-3}$), $\epsilon$ - Dielectric permittivity, $\sigma$ - Electrical conductivity (S m$^{-1}$)

4.2.2 Soils

It was hypothesized that different soil conditions would significantly affect the ability for the GPR to detect SCS. Two soil textures, loam, and sandy-loam were used in the investigation. The two soils were crushed and sieved using a 5-mm screen size sieve and left in atmospheric air conditions to air-dry. The purpose of sieving was to remove relatively large clods and other resistive sediments that may otherwise add variations in GPR predictions. The measurements of soil physical properties were performed at the Iowa State University laboratory. The loam soil consisted of 53% sand, 32% silt, and 15% clay; the sandy-loam soil 58% sand, 26% silt, and 16% clay. According to Holtz and Kovacs (1981), both soils were classified as inactive clays with clay activity values of 0.492 for the loam and 0.723 for the sandy-loam. Although the holding water capacity for both soils were low, the sandy loam had could hold a little bit more VMC compared to the loam. Moreover, the soil textures were categorized as non-saline soils with salinity or electrical conductivity of 0.437 dS m$^{-1}$ for the loam and 0.557 dS m$^{-1}$ for the sandy-loam (Brown, 1998). The soils had soil bulk density and organic matter of 1.28 g cm$^{-3}$ and 3.16% for the loam and 1.40 g cm$^{-3}$ and 3.67% for the sandy-loam. Based on the determined physical properties of each soil texture in the laboratory and the simulation results by Mapoka et al. (2016), GPR was used to detect SCS buried in the two soils. Moreover, a salt solution containing a salt mass of 124 g (density 1.931 g cm$^{-3}$) was added to the sandy-loam and loam soils to change the non-saline soils to saline soils. The treatment was necessary to investigate the effect of saline soils on the GPR waves. The new soil salinity or electrical conductivity parameters measured 3.233 dS m$^{-1}$ for the sandy-loam and 5.238 dS m$^{-1}$ for the loam (see Table 4.2).
Table 4.2  Soil characterization summary

<table>
<thead>
<tr>
<th>Textural class</th>
<th>(%) Sand</th>
<th>(%) Silt</th>
<th>(%) Clay</th>
<th>BD</th>
<th>σ</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loam</td>
<td>53</td>
<td>32</td>
<td>15</td>
<td>1.28</td>
<td>0.44 &amp; 5.24</td>
<td>3.16</td>
</tr>
<tr>
<td>Sandy-loam</td>
<td>58</td>
<td>26</td>
<td>16</td>
<td>1.40</td>
<td>0.56 &amp; 3.23</td>
<td>3.67</td>
</tr>
</tbody>
</table>

OM - Organic matter (%)

Initially, the air-dried soil samples were wetted by adding the same amount of fresh water in each section of the soil bin, and the water was allowed to distribute and equilibrate. Subsequently, the soils were conditioned by thoroughly mixing them for uniform distribution of moisture within each section of the soil bin. Also, the purpose of the exercise was to achieve a 15% to 40% in-field moisture contents for sandy-loam and loam soils prior to data collection (Weiler et al., 1998). Over time the soils naturally dried, and that enabled evaluation of three soil VMC levels per soil type. At the end of each experiment, soil VMC measurements were determined for each soil texture. The dry oven method was used to determine the dry basis moisture content; hence, the soil VMC was calculated using the ratio of soil and water density multiplied by dry basis moisture content. The soil VMC was not controlled in the study; however, the controlled laboratory conditions (temperature and humidity) were critical in regulating soil VMC in the soil bins. Therefore, soil VMC was a random variable that took any quantifiable value during experimentation.

4.2.3  Soil bins experimental setup

Two soil bins were designed and constructed to hold loam and sandy-loam soils. The soil bins measured 1.52 m × 0.88 m × 0.25 m length, width, and height. They were long enough to provide sufficient measurement points within the box. Each box was partitioned into three equal sections measuring 1.52 m × 0.29 m × 0.25 m. In each section, five SCS were buried at a constant depth of 0.076 m (Fig. 4.1). The selected corn depth represents the region between optimal and droughty field conditions of which corn can be planted at a minimum deeper depth of 0.076 m (Hanna, 2013). Also, the soil bins were designed with 0.010 mm holes underneath to facilitate drainage in case of significantly high soil VMC inside the soil bins. Two levelers were designed, measuring 0.13 m and 0.05 m deep, and used to level the soils before and after placement of SCS at the correct depth measurement of 0.076. Additionally, soil bins were constructed with an interchangeable rail track for the GPR antenna cart, Fig. 4.2c. The cart rail measured 1.47 m × 0.18 m × 0.002 m. The rail served
as a spacer between top-soil and the antenna hence elevating the antenna wheels approximately 0.006 m above top-soil, to avoid the antenna plowing into the soil. The spacer distance was maintained throughout data collection to reduce electromagnetic signal energy losses. The rail was designed to be placed within the confines of each soil section from the starting point to the endpoint. Moreover, the cart rail was designed to prevent the cart wheels from ploughing into the soil while collecting data.

Figure 4.1 (a) A schematic layout of the soil boxes and (b) a 2-dimensional schematic side view of a box section with five synthetic corn seeds placed 0.0762 m deep, spaced 0.254 m apart in the soil. The schematic also shows the positive x-direction of the GPR antenna.

Figure 4.2 (a) Empty soil box with three partitioned sections (b) Soil box filled with soil and exposed stainless-steel seeds placed on top at 0.0762 m before covering them with soil (c) GPR cart rail track
4.2.4 Data collection, Processing and Identification of SCS

The laboratory experiments were arranged in a completely randomized design. The primary treatment in the soil bins were the two soil types, three soil VMC, two soil salinity, and SCS (size and type). The GSSI Subsurface Interface Radar-20 (SIR-20) data acquisition and two antenna center frequencies of 1.6 and 2.6 GHz were used (Figure 4.3). Three replicates for each of these treatments in non-saline soils were collected using the 1.6 GHz antenna. A total of 36 experimental test runs were performed. Using the 2.6 GHz antenna a total of five replicates for all treatments were collected with a total of 120 experimental test runs. The targets were spaced 0.254 m, as shown in Figure 4.1b. The sequence in which the two antennas were used was chronological. The antennas were used in the order of the power of their operating frequencies; firstly, the 1.6 GHz was used for all nonsaline soil treatments and secondly, the 2.6 GHz was used for all experimental treatments. The laboratory tests were performed in a controlled-environmental setting (room temperature of 68°F and humidity of 50%). The SCS were manually hand sown in the soil bins, and levelers were used to flatten the soil.

![GSSI SIR-20 System, 1.6 GHz and 2.6 GHz Antenna Controllers](image)

Figure 4.3 GSSI SIR-20 System, 1.6 GHz and 2.6 GHz Antenna Controllers

Signal processing was an essential step in interpreting a GPR radargram, also termed B-scan and commonly presented as a grayscale image. The B-scan image is made up by stitching together a series of A-scans collected from a predetermined spatial distance (Fig. 4.5a). The A-scans (Fig. 4.5b) consist of valuable information that can be extracted through post-processing. Signal processing was performed during and after data collection. Prior to collecting data aluminum sheets were placed at the four corners of the soil bin sections (Fig. 4.4) as a goal to eliminate or minimize noise on GPR B-
scans, improving signal-to-noise within the B-scan. During data collection, signal processing methods and the corresponding parameters were optimized according to specific conditions of the diverse soils in the soil bins. Six time-dependent gains were used, measured in decibels (dB) (Fig. 4.4b) and were optimized accordingly (i.e., trial and error to determine the most efficient gains for the soil conditions and averaging) for each soil type and conditions. It was observed that SCS were detected within the region A and B (see, Fig. 4.4b and Fig. 4.5a). The other two gains on either side (Fig. 4.4b) were relevant but not as crucial for target detection. The time-dependent gain manipulation worked well when adjusted in an ascending manner as shown in the Figure 4.4b. The time-dependent gain points were uniquely variable for each soil type. The gain points enclosing the region A and B were either increased or decreased for adequate detection by a magnitude of 3 dB relative to proximal time gain points. A 3-dB gain increase led to doubled effective amplification of the received waves, which follows that a 6 dB would quadruple the received waves. The manipulation of the time-dependent gain settings effectively enhanced target detection by providing sufficient antenna energy into the soil to delineate the buried SCS from the soil matrix.

RAdar Data Analyzer 7 (RADAN 7) software proprietary to GSSI was used (GSSI, 2003) for post-processing. RADAN 7 has built-in functions that include radargram standardization (time-zero correction - removing the direct current offset and direct current drift), noise filtering tools (noise reduction – finite impulse response, infinite impulse response, horizontal suppression of ringing noise), and signal amplification (gain manipulations feature to enhance visualization). The specific algorithm used in each post-processing analysis varied significantly with radargrams; nonetheless, the convergence was as expected. Consequently, applying appropriate signal processing enabled visualization of SCS, analysis, and interpretation of the radargrams. Moreover, the parameters such as the SCS amplitudes and time to reach the SCS and back to the antenna were extracted for further statistical analysis.

The following approach was adopted to preclude false-positive in our data analysis. The A-scans from the replicates were plotted against each other to identify features that were similar, with some time shift of the features considered. The time features would be handled by adjusting the time-zero to overlay features or adjusting the features to be in-phase with each other (i.e., overlay to assess the commonality and repeatability of features displayed in the A-scans). Any inconsistencies within the features of similar soil conditions could signify random noise or clutter in the soil. Given the same soil conditions, a feature that is repeatable and consistent within the correct nominal time zone
could be used to identify the response feature from the SCS. The A-scan from a different profile or a nontarget profile may be compared with the target A-scan, to avoid the misidentification of the SCS response feature. The feature used to identify the SCS response should not be in that feature of the non-target profile, as shown in Figure 4.5c & 4.5. Moreover, in the radargram (Fig. 4.5a) it was observed that the SCS hyperbolic responses were within the 2 to 3 ns nominal frame time, which was indicated on the overplayed replicate responses (Fig. 4.5c). Figure 4.5d explicitly identifies the SCS feature response while the other response features from the non-target remained the same.

4.2.5 Amplitude normalization

Depending on the explanatory variables, higher gains were used for both collecting and processing data to increase SCS resolution. The SCS response amplitude normalization was performed. That was conducted to yield comparable response amplitudes. Normalizing the response amplitudes provided a degree of certainty that the data being analyzed (amplitude magnitudes) were collected using the same nominal time gain points, eliminating the antenna gain as an independent variable. A linear model was used to normalize the antenna gains per GPR profile collected at different levels of soil moisture content and soil salinity. It was observed in the data sets that targets resided or were detected between two dominant time gain points; hence, the first-order gain model was applied to solve for the standard time gain to be used across to adjust SCS raw amplitude magnitudes. Equation 4.1 & 4.2 below give the first-order gain models for predicting overall time gain with respect to time:
\[ G(t) = A + Bt \] (4.1)

\[ G(t_d) = A + Bt_d \] (4.2)

where \( G(t) \) and \( G(t_d) \) are antenna gains at time \( t \) and \( t_d \) in nanoseconds (ns), \( t = 0, 1, 2, 3, 4, \ldots, N \), \( A \) and \( B \) are estimated coefficients, and \( t_d \) is actual two-way travel time (TWTT). In most cases recorded targets were detected within \( G(t) = G(2) \) and \( G(t) = G(3) \), resulting in simultaneous equations that can be solved for \( A \) and \( B \), thus calculating the normalized gain at \( t_d \), Equation 4.2. The normalized gain was subsequently used to rescale the raw amplitude to the baseline using the amplitude ratio conversion function, Equation 4.3:

\[ A_{\text{new}} = A_{\text{old}} \times 10^{\frac{G_{dB}}{20}} \] (4.3)

where \( A_{\text{new}} \) and \( A_{\text{old}} \) are the new rescaled and old (raw) amplitude magnitudes, \( G_{dB} \) is expressed as the difference between the new gain, \( G(t_d) \), and the old gain used to collect B-scan data, \( G(t+1) \). Equation 4.3 was derived from signal amplitude attenuation. Note that the response amplitude magnitude represents the detection of the SCS.

### 4.2.6 Estimation of Two-Way Travel Time (TWTT)

Experimental tests were conducted in a laboratory setting, and GPR B-scans in realistic situations were obtained and processed. The location of the hyperbolic apex was critical, as from the apex point the response amplitudes and total time (\( t_T \) - wave time to reach the target and back to receiver) were extracted by identifying a window at the vertex coordinates of the hyperbolic response as shown in Figure 4.5a. The \( t_{FW} \) marks the first instance where the GPR wave penetrated the soil (Fig. 4.5a). The time difference between \( t_T \) and averaged \( t_{FW} \) provided the two-way travel time between the top subsoil surface and the SCS surface, \( t_d = t_T - t_{FW} \). Moreover, for each target detected A-scans were extracted and their values plotted in Excel (Fig. 4.5b). The averaged crossover time \( t_{FW} \), front wall time) was computed from the four hyperbolic responses (Fig. 4.5b).
Figure 4.5 Raw 1.6 GHz GPR data: (a) B-scan showing $t_{FW}$, $t_T$, and $t_d$ parameters and (b) A scan plot for the four medium synthetic metal seeds detected from the sandy-loam soil, (c) overlaying feature responses for the inidentification of common features, and (d) identification of the SCS response to avoid false positive. NB: Target A-scan is a representative of the three replicates and Rep is replicate.

4.2.7 Estimation planting depth (PD)

Conversion of GPR two-way travel time to depth is only possible when the wave velocity through the soil is computed. The process of calculating the wave velocity aims at calibrating or correct the material velocity for accurate depth predictions (Conyers, 2013). To estimate PD’s, three relevant parameters, the $t_d$ in nanoseconds (ns), the dielectric permittivity ($\epsilon$), and the speed of light ($c = 3 \times 10^8$ m/s), are needed as shown in Equation 4.4. The TWTT was computed as explained in the estimation of $t_d$ above. In addition, three approaches to predict the dielectric permittivity of the soils were introduced. The three approaches were Topp’s dielectric model (Topp et al., 1980), soil mixing model (Peplinski et al., 1995) and a constant dielectric model. Topp’s dielectric equation considers the soil VMC to estimate the dielectric permittivity. With this method, uncertainties may be prevalent. Free water has high dielectric permittivity, which has the potential to influence soil dielectric permittivity. The technique relates the soil dielectric permittivity with measurements
under relaxation frequency of free water in the soil (Topp et al., 1980), but does not consider water that is held tight between soil particles or bond water within the soil matrix, which can reduce the overall dielectric permittivity. Also, this method does not consider other soil parameters, such as soil density and soil composition; it excludes the frequency-dependent behavior in the prediction of the soil dielectric permittivity. However, the main idea of using Topp’s dielectric equation was to lessen the error effect that might arise from soil VMC to PD error estimation as the influence from VMC would have been factored in when calculating soil dielectric permittivity. The Topp’s dielectric equation has high fidelity in the prediction of soil dielectric permittivity.

Peplinski et al. (1995) developed the soil mixing model that factors in the potent soil physical properties: soil bulk density, soil composition, soil moisture, frequency-dependent behavior, and pore space to predict soil dielectric permittivity. The method, however, does not factor in the bond water and organic matter, which can improve estimation of the soil bulk dielectric permittivity. For instance, an increase in the bond water and specific surface area in clayey soils leads to a decrease in soil bulk dielectric permittivity. Organic matter increases the specific surface area of soils. High organic content in the soil leads to lower soil dielectric permittivity. Compared with Topp’s prediction, however, the uncertainty associated with the soil mixing model may be minimal, because the soil mixing model uses several soil parameters.

Nonetheless, these two empirical methods (Topp’s dielectric and soil mixing models) have been widely used in agriculture for decades to estimate soil dielectric permittivity. The PD error predictions calculated from the two dielectric permittivity models were compared in a quantitative manner side-by-side, and overall sums of square errors were computed for each method. Each of the determining parameters (e.g., soil moisture, soil composition, and frequency) may also affect the depth error measurement variability for each method.

The third method uses an ‘extrapolated’ constant dielectric permittivity (selected based on the above two empirical methods) across a soil texture. The constant dielectric parameter assumed that the dielectric permittivity of the soil was constant, and not affected by soil composition, density or volumetric moisture content. Finally, the measured GPR PD ($D_e$) is estimated using Equation 4.4.

\[ D_e = \frac{ct_d}{2\sqrt{\varepsilon}} \]  

(4.4)
4.2.8 GPR measurement error (ME)

The measurement error was calculated as the difference between the known depth \( D_0 \) and the GPR estimated depth \( D_e \), as shown in Equation 4.5. The measurement error could be thought of as the coefficient of planting depth accuracy (CPDA) which represents the measurement variability from the mean. The introduction of CPDA was to assess the effectiveness and accuracy of the GPR in the prediction of the SCS PDs. The CPDA indicates the deviation (i.e., measured in meter or centimeter or inches) of \( D_e \) relative to \( D_0 \). The percent GPR measurement error was computed by taking the ratio of CPDA and the \( D_0 \), as shown in Equation 4.6. The absolute percent ME ranges from zero to unity (0 to 1), whereby values proximal to zero would reflect an acceptable, recommendable CPDA, and the efficacy of the GPR on the proximal approximation of the SCS PD. Conversely, a value close to unity would reflect the worst CPDA and ineffectiveness of the GPR sensor to measure the SCS PD. In this study, the acceptable nominal CPDA for our analysis was a value less than \( \pm 0.005 \) m. The nominal CPDA was based on the planters depth adjustment, which is graduated a quarter inch (0.00635 m) per each increase or decrease. Therefore, a lower ME would imply a minimal deviation from the known theoretical depth or CPDA.

\[
CPDA = D_0 - D_e \tag{4.5}
\]

\[
ME(\%) = \left( \frac{CPDA}{D_0} \right) \times 100(\%) \tag{4.6}
\]

4.2.9 Data analysis

Statistical software JMP Pro 13 was used to perform multiple linear regression analysis to evaluate the effects of the explanatory variables VMC, soil type, soil salinity, seed material, and seed size on estimating the PD error. Mallow’s \( C_p \) (Fujikoshi and Satoh, 1997) was used to select the best regression model. The data included some rows with no SCS responses (whereby the GPR could not detect the SCS); these rows were excluded in the multiple regression. Thus, a logistic regression was used to include the rows that had no responses. Furthermore, the CPDA was used to examine the GPR efficacy in predicting the depth with minimal error compared to the theoretical planting depths.
4.3 Results

4.3.1 1.6 GHz antenna

The 1.6 GHz GPR was used to detect Synthetic Metal Seeds (SMS), and Synthetic Wood Seeds (SWS) buried shallow in non-saline sandy-loam and loam soils. The data was collected on three separate occasions whereby on average three soil VMCs for each soil type were successfully investigated. The measured VMCs (d.b.) were 13%, 17%, and 24% for the sandy-loam, and 5%, 11%, and 15% for the loam soil. The soil VMCs indicated that the sandy-loam had higher moisture holding capacity compared to loam. The discrepancy in soil VMCs between the two soils were due to the difference in the clay content, and the original soil VMCs were greatly different. The loam had excessively lower soil VMC compared to the sandy-loam.

The raw B-scans (radargrams) in Figure 4.6 & 4.7 were presented as measured with the sample time rate of 0.0045 ns (time window of 5 ns). The radargrams presented were from a single moisture group (low VMC) with respect to soil type. The data illustrates the significance of the SCS size and material effect on the detection. The radargrams show the SCS buried at a constant depth of 0.0762 m. The critical feature to identify the SCS in the radargrams was the SCS hyperbolic signatures. The radargrams in Figure 4.6 & 4.7 are from the SMS, and it was evidently clear that the bigger the SCS, the easier it was for the 1.6 GHz antenna to detect. It was observed on the radargrams that the hyperbolic responses for the medium and large SMS were visible and accessible to interpret in sandy-loam and loam at all soil VMCs. Not much of the processing (e.g., filtering or suppression of the ringing noise) was necessary due to strong hyperbolic signatures for the medium and large SMS (Fig. 4.6b & c and Fig. 4.7b & c). The radargram quality, however, was observed to be lower particularly for the small SMS, Figure 4.6a & 4.7a. The 1.6 GHz antenna had difficulties detecting small SMS. The hyperbolic responses were not evident in the radargrams, which led to the RADAN 7 advanced processing steps to improve the interpretability of the data. The implication was, the effect of the SMS size and to some extent, the clutter that was within the soil played a significant role in concealing the small SMS targets.

As for the SWS, neither target size was detected in the same soil conditions as the SMS. Thus, the use of the 1.6 GHz was terminated after one treatment level of soil salinity (non-saline) was investigated. In addition, it was observed in the data collected that the hyperbolic response from one of the first SMS was truncated; henceforth, the processing and analysis were performed on the
Figure 4.6 Raw radargrams from a 1.6 GHz antenna (a) small, (b) medium, and (c) large SMS in non-saline sandy-loam soil

four SMS hyperbolic responses that were fully defined (with 216 rows of data). The size and material had a significant effect on the detectability of the SMS. It was easier to detect medium and large SMS in both soils, as evidently shown in Figure 4.8. Moreover, the electrical conductivity of the SMS (conductor) had an enormous impact on the GPR wave reflectance which made it easier to detect the SMS targets than it was to detect the SWS targets. Particularly at higher soil VMC (wet soil matrix surrounding the SCS), it was evident that the effectiveness of the 1.6 GHz antenna wave gradient decreased. A higher number of small SMS were detected in loam compared with sandy-loam soil, partly because of its lower VMCs. Of the three replicates for small SMS (12 SMS), 10, 9, and 0 SMS were detected in loam with VMCs of 5%, 11%, and 15%, respectively, compared with 9, 6, and 0 SMS detected in sandy-loam with VMCs of 13%, 17%, and 24%, respectively. The detection rate was 100% for medium and large metal seeds regardless of soil type and soil moisture
Figure 4.7 Raw radargrams from a 1.6 GHz antenna (a) small, (b) medium, and (c) large SMS in non-saline loam soil

contents. However, for small metals targets, the detection rate was 42\% and 53\% in sandy loam (at 13\% to 17\%) and loam (at 5\% to 11\%), respectively.

The identification of the SCS was performed; hence, the response amplitudes and the TWTTs of each target were extracted. The TWTTs and normalized SMS response amplitudes are plotted against the SMS sizes for each soil type and each VMC. The response amplitudes and TWTTs were averaged from three replicates (12 target SMS), and the corresponding sample standard deviations are represented as error bars in Figure 4.8 & 4.9. Note that no response was available for the small targets buried in soils with highest VMC. Also, Figure 4.8 shows that for both dry sandy-loam and loam soils the SCS had higher response amplitudes. Figure 4.9 shows that TWTTs were higher for sandy-loam soil (low GPR wave transmission speed to reach the SMS targets), partly due to VMC differences between the two soils.
4.3.2 2.6 GHz antenna

Since the small SMS were not detected by the 1.6 GHz antenna the 2.6 GHz antenna was used to detect small SMS, and SWS (medium and large) buried shallow (0.9762 m) in sandy-loam and loam soils. The data collection was conducted as above; however, five experimental replicates for each SCS size and type were performed, and two salinity treatment were investigated. Three soil VMCs
were investigated in non-saline and saline soil conditions per soil type. The evaluated VMCs were 12%, 15%, 25% non-saline sandy-loam, and 13%, 19%, and 31% saline sandy-loam. The non-saline loam was evaluated at 11%, 16% and 24%, and saline loam at 12%, 19%, and 30%.

The radargrams presented in Figure 4.10 to 4.12 are used as examples and were collected from the sandy-loam soil. The raw radargrams in Figure 4.10 (non-saline soil) and Figure 4.10a (saline soil) were collected and presented as measured with the sample time rate of $\sim 0.0034$ ns (time window of 3.5 ns and 4 ns, respectively). The radargram data represents SCS buried at 0.0762 m and their signatures. The radargrams were noisy, and quality of SCS hyperbolic signatures were significantly weak.

Figure 4.10 Raw GPR data from a 2.6 GHz antenna from non-saline sandy-loam at low soil VMC (a) small SMS, (b) large and (c) medium SWS

Figure 4.10a has visible hyperbolic response and the processing of an image was not advanced compared to Fig. 4.10b & 4.10c. Processed radargrams of Figure 4.10b & 4.10c are shown in Figure 4.11a & 4.11b, respectively. It was evident that after processing a few SWS targets were
visible. However, the level of difficulty to enhance the hyperbolic responses on the radargrams was correlated with the size of the SWS. A clear hyperbolic response from the SWS was not possible to attain even after processing, with medium SWS response being complicated to enhance. In some cases, multiple responses after processing and strong hyperbolic responses from artifacts were observed (Fig. 4.11b). The subscript number on SWS (e.g., \(SWS_1\)) represents the number of the detected SWS in the radargram. In Figure 4.12b hyperbolic responses of the SWS were not visible in saline soils; however, the small SMS were partially visible. The same phenomenon was observed on the loam soil.

Figure 4.11  The processed radargrams from a 2.6 GHz antenna collected from nonsaline sandy loam at low soil VMC (a) large and (b) medium SWS.

Figure 4.12  GPR data from a 2.6 GHz antenna in saline sandy-loam at low soil VMC (a) raw radargram, and (b) processed radargram.
The expected number of detected targets across all five replicates per SCS size in different soil conditions was 75 (5 replicates × 5 SCS × 3 soil VMC × 1 saline level = 75 detected SCS). The exact number of detected SCS with respect to soil VMC and salinity are presented herein. In the non-saline sandy-loam soil, 25, 25, and 19 small SMS, 15, 9, and 0 medium SWS, and 20, 15, and 0 large SWS were respectively detected at 12%, 15%, and 25%, soil VMCs. At higher soil VMCs, the medium and large SWS were not detected. In the saline sandy-loam soil, 14, 8, and 6 small SMS, 2, 0, and 0 medium SWS, and 6, 0, and 0 large SWS were detected corresponding to 13%, 19%, and 31% soil VMCs. In the non-saline loam soil 25, 25, and 24 small SMS, 20, 0, and 0 medium SWS, and 25, 5, 0 large SWS were detected in 11%, 16% and 24% VMC, respectively. While in the saline loam soil, 16, 10, and 0 small SMS, 0, 0, and 0 medium SWS, and 7, 0, and 0 large were detected in 12%, 19%, and 30% VMC, respectively, as illustrated in Figure 4.13 to 4.16. The detection rate varied with soil salinity, VMC, and soil type. At the lowest soil salinity and VMC the detection rate of SCS was higher and evident on the radargrams. An increase per each level treatment negatively impacted detection, as shown in Table 4.3 & 4.4.

Table 4.3 Detection rate in non-saline sandy loam and loam soils with metal and wood seeds

<table>
<thead>
<tr>
<th>Sandy loam soil</th>
<th>Loam soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMC(%)</td>
<td>SM(%)</td>
</tr>
<tr>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>12</td>
<td>100</td>
</tr>
<tr>
<td>15</td>
<td>100</td>
</tr>
<tr>
<td>25</td>
<td>76</td>
</tr>
</tbody>
</table>

SM - small metal, LW - large wood, and MW - medium wood targets

Table 4.4 Detection rate in saline sandy loam and loam soils with metal and wood seeds

<table>
<thead>
<tr>
<th>Sandy loam soil</th>
<th>Loam soil</th>
</tr>
</thead>
<tbody>
<tr>
<td>VMC(%)</td>
<td>SM(%)</td>
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<tr>
<td>-----</td>
<td>-----</td>
</tr>
<tr>
<td>13</td>
<td>56</td>
</tr>
<tr>
<td>19</td>
<td>32</td>
</tr>
<tr>
<td>31</td>
<td>24</td>
</tr>
</tbody>
</table>

Small SMS were detected in non-saline soils. In two of these soils, detecting the medium SWS was determined to be difficult at the highest and intermediate VMC; however, for less than 15% VMCs, there was substantial evidence that the 2.6 GHz can detect medium SWS, as observed in Figure 4.13. Higher VMC increase soil impedance, which in-turn impeded GPR wave propagation,
and, due to the ionic concentration and movement, the attenuation of the waves was the highest. Saline soils were not favorable to GPR waves. A combination of higher soil saline level and VMC reduced the 2.6 GHz antenna power gradient to detect the SCS when compared to the non-saline condition. The number of SCS detected plummeted to zero at higher VMC; also, when the soil salinity in sandy-loam and loam was higher. The SWS were infrequently detected at low VMC in saline soils, while in saline soils and higher VMCs, neither SWS was detected (Fig. 4.15).

The implication arising from the results suggested that GPR waves are ineffective in higher soil salinity and VMC. This was attributed to the higher soil permittivity and potential ionic concentration arising from soluble salt. Therefore, subjecting GPR waves to such soil conditions may have led to total polarization and attenuation of the waves within the soil. The size and material had a substantial effect on the detectability of the SCS. Larger SWS targets were easily distinguished compared to medium counterparts in both soils, and material dielectric properties added advantage towards detection. It was more likely to detect small SMS than it was to detect either size of the SWS in certain soil conditions. The normalized amplitude responses and TWTTs were shown in Figure 4.13 & 4.15, and Figure 4.14 & 4.16, respectively. The response amplitudes and TWTTs were averaged from five replicates, and error bars correspond to the sample standard deviations.

Figure 4.13  Response Amplitudes of the 2.6 GHz antenna for small SMS, and SWS in (a) non-saline sandy-loam soil and (b) non-saline loam soil
Figure 4.14  two-way travel time responses of the 2.6 GHz antenna for small SMS and SWS in (a) non-saline sandy-loam soil and (b) non-saline loam soil

Figure 4.15  Response Amplitudes of the 2.6 GHz antenna for small SMS and SWS in (a) saline sandy-loam soil and (b) saline loam soil
Figure 4.16 Two-way travel time responses of the 2.6 GHz antenna for small SMS and SWS in (a) saline sandy-loam soil and (b) saline loam soil

4.4 Statistical Analysis

4.4.1 The 1.6 GHz antenna

A full factorial multiple regression was performed on the estimated depth measurement error (ME). The ME estimated using the constant dielectric permittivity was predicted with an $R^2$ of 0.69 and root mean square error (RMSE) of 7.85%. The ME estimated using the soil mixing model method was predicted with an $R^2$ of 0.87 and RMSE of 8.42%, and the Topp’s dielectric model was predicted with an $R^2$ of 0.95 and RMSE of 5.98%. The Topp’s dielectric model predicts the lowest percent error and prediction variables are shown in Table 4.5. During the experimental soil sensing tests, the SMS were successfully detected by the 1.6 GHz GPR. Therefore, the developed model (Table 4.5) pertains to the SMS.
Table 4.5  Topp’s dielectric model parameter estimation for all the SMS (1.6 GHz antenna)

| Term                        | Estimate  | Std Error | t Ratio | Prob > |t| |
|-----------------------------|-----------|-----------|---------|---------|
| Intercept                   | -29.55562 | 1.899725  | -15.56  | <.0001* |
| soil type[Lo]               | 32.591675 | 0.751608  | 43.36   | <.0001* |
| seed size[L]                | 4.5647101 | 2.147633  | 2.13    | 0.0350* |
| seed size[M]                | 8.2058278 | 2.147633  | 3.82    | 0.0002* |
| vmc                         | 1.9151854 | 0.152106  | 12.59   | <.0001* |
| seed size[L]:vmc           | -0.488315 | 0.174917  | -2.79   | 0.0059* |
| seed size[M]:vmc           | -0.817663 | 0.174917  | -4.67   | 0.0001* |
| soil type[Lo]:seed size[L]:vmc | -0.298886 | 0.063601  | -4.70   | 0.0001* |
| soil type[Lo]:seed size[M]:vmc | -0.487609 | 0.063601  | -7.67   | 0.0001* |

*Significant

4.4.2  The 2.6 GHz antenna

A full factorial multiple regression analysis was performed, and the data was grouped according to seed type. The interactions that were not significant to the model were removed from the analysis. For the small SMS, the constant dielectric permittivity had an $R^2$ of 34% and RMSE of 5.84%. The soil mixing model had an $R^2$ of 54% and RMSE of 6.74%, and Topp’s dielectric model had $R^2$ of 27% and RMSE of 9.80%. For the SWS, the constant dielectric permittivity had an $R^2$ of 25% and RMSE of 6.12%. The soil mixing model had an $R^2$ of 13% and RMSE of 7.34%, and Topp’s dielectric equation had $R^2$ of 38% and RMSE of 7.86%.

The methods presented for the SMS and SWS are both close in accuracy with their average ME of 7.46% and 7.11%, respectively. Therefore, the implication could be that all methods can be equally used to estimate ME. However, further model selection criterion needed to be examined. Stepwise regression was performed to identify the best model. The models were selected based on the Mallow $C_p$ criterion, $C_p \leq p$. From the stepwise criterion, the soil mixing model (Table 4.6) was determined to be the best model with $C_p \leq 2.05$ and $p = 3$ for small SMS ME predictions. Furthermore, Topp’s dielectric model (Table 4.7) was found to be substantially useful in predicting the error with $C_p \leq 3.94$ and $p = 4$ for SWS ME predictions. The coefficient of determination and RMSE were unchanged for both the methods.
Table 4.6  Soil mixing method parameter estimation for SMS ME (2.6 GHz antenna)

| Term                | Estimate | Std Error | t Ratio | Prob > |t| |
|---------------------|----------|-----------|---------|---------|
| Intercept           | 20.12    | 1.60      | 12.60   | <0.0001* |
| soil type[Lo]       | -3.08    | 0.49      | -6.33   | <0.0001* |
| vmc                 | 0.02     | 0.09      | 0.21    | 0.8313   |
| salinity level[Nonsaline] | 2.74    | 0.55      | -4.94   | <0.0001* |

*Significant

Table 4.7  Topp’s dielectric method parameter estimation for SWS ME (2.6 GHz antenna)

| Term                | Estimate | Std Error | t Ratio | Prob > |t| |
|---------------------|----------|-----------|---------|---------|
| Intercept           | 72.96    | 7.89      | 9.25    | <0.0001* |
| soil type[Lo]       | -2.08    | 0.95      | -2.19   | 0.0307*  |
| seed size[Lw]       | 2.84     | 0.84      | 3.40    | 0.0009*  |
| vmc                 | -4.99    | 0.66      | 7.54    | <0.0001* |
| salinity level[Nonsaline] | 1.18    | 1.21      | 0.97    | 0.3338   |

*Significant

The Topp’s dielectric model in Table 4.7 has three significant predictor variables: soil type, seed size, and soil VMC, to predict the error with the salinity variable being less significant. For this analysis, there were data rows with no points from which they were excluded in the analysis; therefore, the effect of salinity would never have been captured in this statistical analysis. Similarly, the expectation would be that the VMC should be less significant in the Topp’s dielectric model.

4.4.2.1 Logistic regression and sensitivity analysis (profiler analysis)

The SMS were readily detected in sandy-loam and loam soils. The difficulty was detecting SMS in saline and higher VMC soils. The SMS were used primarily as a benchmark for our investigation. However, in this section, the appropriate emphasis is directed towards the detection of SWS. The reason for that was the SWS have properties that are relatively similar to the agricultural corn seeds in terms of their dielectric permittivity, as previously discussed. Moreover, the primary objective of the research leads to the detection and estimation of the planting depth of the agricultural corn seeds in future research. Therefore, only SWS results are discussed below. The effect of soil VMC, salinity, type, and 2.6 GHz antenna on detection of SWS were thoroughly investigated and are discussed herein.
4.4.2.2 The effect of soil VMC and salinity on detection

The highest detection of SWS was at lowest soil VMC and nonsaline soils. SWS could still be detected in saline sandy-loam and loam soils at the lowest VMC. When soils are dry, the net ionic movement within the soil did not exist which meant the waves could find their way to the target. Though the detection was observed, the SWS responses were still weak. The profiler provided the sensitivity analysis; whereby, it demonstrated the sensitivity of the predictor variables, as one parameter was varied while holding the other variables constant. The exercise was conducted for optimization purposes. The soil VMC and salinity interaction had an adverse effect on the detection of SWS, as it contributed to a significant drop in the detection of SWS. Saline soils made it challenging to detect SWS. Also, a rapid exponential decrease in detection of SWS was observed as soil VMC was increased both in sandy-loam and loam soils. At lower soil VMCs, and non-saline soils, the SWS were substantially detected by the GPR. Therefore, the practical strategy for future research on measuring planting depth may be to investigate these conditions using real agricultural corn seeds.

4.4.2.3 The effect of soil type and SWS size

There was no statistical difference in the detection between the loam and sandy-loam soil. Provided with the same soil conditions and SWS, and using a 2.6 GHz antenna, the ability to detect either target in loam and sandy-loam were 41.7% and 45.6%, respectively. The two soils had approximately the same clay content. The detection was more difficult when the size of SWS were decreased (the bigger the SWS, the easier it was to detect in certain soil conditions), and in cases where the contrasting dielectric property was not substantial.

4.4.3 Discussion

This proof of concept study was executed under controlled laboratory conditions, and the use of the GPR was successfully implemented to locate buried SCS in sandy-loam and loam soils. The ability to detect and accurately estimate SCS planting depth using a nondestructive GPR was an essential aspect of the continuum of this research work. The objective was to use the GPR to detect SCS buried at a constant depth of 0.0762 m. Two antenna frequencies 1.6 and 2.6 GHz have been evaluated in different soil conditions. The dielectric contrast of agricultural CS and surrounding
soil matrix is relatively unknown. The utilization of SCS provided a better understanding of the surrounding soil matrix and SCS. The knowledge gained in this study may play an essential role in the detection of real agricultural corn seeds (ACS).

The 1.6 GHz antenna was only able to detect the SMS and had difficulties in detecting small SMS in certain soil conditions (Fig. 4.6 to 4.8). Furthermore, the 1.6 GHz antenna failed to detect the SWS buried in the same soil conditions as were the SMS. The failure to detect SWS was attributed to the antenna wavelength and the resolution (sensitivity) of the antenna to distinguish the dielectric SWS from the soil. Initially, the SWS were buried dry and were kept in the moist soils for a period of time. It could be assumed that the SWS imbibed soil moisture from the surrounding soil matrix during the course of the experimentation as the soil dried. However, with the slight increase of SWS moisture, the 1.6 GHz antenna was not capable of detecting the SWS. Therefore, further investigations with the 1.6 GHz antenna could not be continued, and no further statistical interpretation was necessary.

This study has shown that the 2.6 GHz antenna was capable of detecting both medium and large SWS in the artificially prepared soil bin. The capability of the 2.6 GHz to detect SWS in the two soils at varying conditions was beneficial and critical towards advancing our work to map ACS. The 2.6 GHz antenna was met with mixed success in detecting the SWS. Just as above, the SWS were initially dry, and they absorbed the moisture from the surrounding soil during data collection. As the soil drained and dried-up around the SWS, the dielectric contrast between the SWS and the soil was significant which lead to the detection of the targets. The implication would be to soak the SWS in water just enough to hold moisture content from 11.00% to 14.00% (CS moisture at planting, (Sayre, 1940)), and burying them in drier soils; the dielectric contrast could be more substantial for the GPR detection.

Three methods were used to estimate the dielectric permittivity, which were used to predict SCS depth: constant dielectric, soil mixing model, and Topp’s dielectric model. The assumption was, the constant dielectric was not affected by the soil physical properties (soil texture, composition, soil VMC) and it was observed using extreme constant dielectric permittivity values compared to the predicted dielectric permittivity from Topp’s dielectric and soil mixing models the ME’s that were computed were overwhelmingly large. Yet, extrapolating dielectric permittivity values proximal to the two models (Topp’s dielectric and soil mixing) ME’s were significantly reduced. Therefore, these three predictive methods can equally be employed to estimate the dielectric permittivity to calculate
PD with minimal ME. However, the stepwise regression conducted showed that the Topp’s dielectric model was the best at predicting the planting error for the SWS with RMSE of 7.86%. Based on the estimated SWS ME, the comparison between these methods was performed; hence, enabling us to obtain optimal soil physical properties that are more appropriate for the GPR to detect SWS successfully. The results obtained in this research, however, are preliminary and the data in this finding was from prepared soils and SCS in the laboratory. Therefore, more future research needs to be performed to validate the model determined, for the detection and depth predictions for agricultural corn seeds. The nondestructive 2.6 GHz GPR showed that it might further be employed as an alternative for detecting and estimating ACS. However, caution needs to be practiced to achieve the desired results in different soils. For future research, the initial experimental setting may incorporate the soil conditions that resulted in the SWS to be distinguished in the sensing investigation using the 2.6 GHz, and perhaps a slightly higher GPR antenna frequency.

4.5 Conclusion

In this investigation, target detection of SCS using a ground penetrating radar (GPR) of 1.6 and 2.6 GHz antenna frequencies for the estimation of the ME has been demonstrated. The statistical regression procedures were performed to build an optimal model that examines the effect of the soil conditions and synthetic corn seed properties in the detection. The project objectives were met, and the following conclusions were made from this study:

- Synthetic metal seeds targets were distinctively responsive to 1.6 and 2.6 GHz at varying soil types (loam and sandy-loam) and conditions (soil VMCs, textures, and non-saline/saline). Additionally, the synthetic target material type and size had a noticeable impact on their detection (sizable and conductive or substantial dielectric contrast better detection).

- Higher soil salinity and VMC rapidly attenuated the GPR waves which led to neither detection of the synthetic corn seeds.

- Three methods were used to correct for the GPR wave velocity: Topp’s dielectric, soil mixing, and constant dielectric model. The Topp’s dielectric model was determined to be the most efficient model. The prediction of synthetic wooden seeds planting depth and measurement error was 7.86%. The measurement error significantly close to the stated CPDA which suggested that CPDA was acceptable relative to the theoretical depth.
• As observed from the results, particularly for synthetic wooden seeds, the imbided moisture had a dramatic effect in the detection, which may imply since agricultural corn seeds have 8% to 14%, there might be a possibility to detect them in dry soils. However, should that result to no detection, the dielectric properties of corn seeds (i.e., agricultural corn seeds) may need careful and harmless alteration to improve GPR detection.

References


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CHAPTER 5. APPLICATION OF GROUND-PENETRATING RADAR IN MEASURING CORN SEED SPACING AND PLANTING DEPTHS IN DIFFERENT SOILS

A paper modified from a manuscript published in the 2018 ASABE Conference Proceedings

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Abstract

The corn seed spacing and planting depth effects have been well researched. Correct seed spacing and planting depth may enable sufficient moisture absorption for germination and eliminate the plant hierarchy structure. Measuring seed spacing and planting depths in a closed furrow is necessary for precision seeding enhancement. In agricultural applications, ground penetrating radar is used for nondestructive evaluations as a potential sensor to maximize the qualitative and precision or repeatable assessments in long-term research. Yet, the ground penetrating radar system has not been used to measure seed spacing and planting depths, but it has the potential to measure the two parameters. The objective of this experimental research was to use a non-destructive 2.6 GHz ground penetrating radar system to detect agricultural Corn Seeds (CS) buried at three depths (3.81, 6.35, and 8.89 cm) and two spacing (15.24 and 25.4 cm) in sandy-loam and loam soils. The data was processed using the Fast Discrete Curvelet Transform to denoise and enhance edge responses from CS. In dry soils, some CS were detected, while in intermediate and moist soils it was difficult to detect CS. The two-way travel time in nanoseconds and soil dielectric permittivity from experimental data were used to estimate planting depth while the spatial distance between the CS was computed from the antenna cart encoder. The Topp’s dielectric, soil mixing, and the Topp-Mixing (TM) model were used to estimate the soil dielectric permittivity. The TM model was developed as a function of the Topp’s dielectric, and soil mixing models to minimize and optimize planting depth measurement error, by correcting the wave velocity. The TM model was found to be effective in predicting permittivity used to approximate planting depth with minimal measurement.
error. The assessment of the 2.6 GHz antenna effectiveness was based on the percent coefficient of precision (CP3) and coefficient of planting depth accuracy (CPDA). The CP3 values were less than 30% but differed for the three moisture groups and soil types. The TM model had the best CPDA of 8.37%. The results in this study are promising, but more research is needed to enable detection and depth measurements of CS in soil conditions that are typical of a plowed field.

Keywords Corn seeds, CPDA, GPR, Planting Depth, Topp-Mixing, Dielectric permittivity

5.1 Introduction

The corn seed spacing and planting depth effects have been well researched. The corn seeds (CS) can be planted at depths ranging from 3.81 cm to 8.89 cm and spaced 13.97 cm to 25.40 cm depending on the soil abiotic factors (particularly soil moisture content, and texture), variety and soil water holding capacity. Correct CS spacing and planting depth may enable moisture absorption for germination and eliminate the plant hierarchy structure. Liu et al. (2004) emphasized the fact that corn was more responsive to the emergence variability rather than in-row spacing variability. The study also indicated that corn emergence variability reduced the total yield while the in-row spacing did not have an effect on the yield. However, agronomists and producers agree that uniform in-row spacing and depth control at planting provide the highest probability to achieve the maximum yield (Andrade and Abbate, 2005). The importance of plant spacing and depth is reflected in the development and publications of the ISO Standard 7256/1, developed to assess the performance of planters, i.e., measuring actual seed spacing and determining the uniformity of trench depth and seed depth (ISO, 1984; Koller et al., 2014).

Dielectric properties refer to inherent constitutive characteristics of a material which govern the electromagnetic behavior of the propagated wave through a material. CS are dielectric composites that have no free moving charges within their cellular membrane. It is well known that water molecules influence dielectric properties; therefore, for any material that possesses any amount of water, a range of dielectric constants can be exploited. The latter applies to CS, where, at storage, their moisture ranges from 5% to 14%. This moisture limit creates an environment whereby microwave frequencies can be used to determine CS moisture noninvasively without compromising the grain quality (Nelson, 2005). The moisture content which influences the dielectric component of the CS, may play a crucial part in the detection. This research work focusses on quantitatively
measuring CS planting depth and spacing using non-destructive Ground Penetrating Radar (GPR) technique. In numerous GPR studies or surveys, the dielectric features of agricultural materials are frequently the response variables; however, targets of that nature (dielectric) are often not good reflectors. The CS size and orientation in the soil may be a factor that can remarkably impact their detectability using the GPR.

A simulation study was performed by Mapoka et al. (2016) to evaluate the possibility of using GPR to map models of synthetic target (metal having the same dimensions as CS), and CS (having properties of real seeds). The GPR model of antenna frequencies of 1.6 and 2.6 GHz successfully detected the modeled synthetic targets as well as modeled CS having approximately the same dielectric properties as the real corn seed. The response amplitudes were substantial except in conditions where the soil models had higher clay content, bulk density, and highly conductive. In addition, Chapter 3 reports that at lowest soil moisture levels there was no substantial dielectric contrast between the corn and soil model, which led to low amplitude responses. Chapter 4 describes the experimental work that focused on using synthetic corn seeds, two soil types and GPR antenna frequencies. The results showed that higher antenna frequency performs better than lower antenna frequency in detecting dielectric targets. Chapter 4 also presents the soil properties that were investigated and their consequential impacts. GPR waves are sensitive to abrupt changes of the material constitutive (electrical properties) conditions, which leads to inevitable multiple non-uniform and intermittent scattering within the subsurface. The GPR images convey the positions of the buried targets in terms of hyperbolic responses; therefore, a high attenuation medium or multiple intermittent reflection may profoundly reduce GPR image resolution and target responses quality. The latter may negatively impact the data analysis and interpretation.

In this research, the overall performance of the GPR was assessed using the measured corn spacing and planting depth. The capability of measuring corn spacing and planting depth using the GPR may have an essential contribution in precision seeding to maximize corn production. The objective was to use a 2.6 GHz GPR antenna to map CS buried at three different planting depths and two spacing in different soil types and conditions. The GPR waves were evaluated in sandy-loam, and loam soils at three soil volumetric moisture content groups. The corn spacing and planting depth were quantified using the antenna wheel encoder and the GPR depth law (Equation 5.4), respectively.
5.2 Materials and Methods

5.2.1 Soils

The sandy-loam and loam soils were used in the investigation. The sandy-loam was collected from the Applied Science Iowa State University farm (Moore), Ames, Iowa (Latitude 42.043564 N, Longitude -93.659040 W). The loam soil was collected from Iowa State Farm, in Boone County, Iowa (Latitude 42.021196 N, Longitude 93.773627 W), with which the soil series in the farm were the Clarion (66.11 ac), Canisteo (35.76 ac), and Nicollet (31.63 ac) (Andrews, 1981). The soils were collected from a depth range of 0 to 40 cm. The sandy-loam and loam soils were sieved using a 5 mm sieve to reduce the clutter that might otherwise prevent corn seed detection.

Due to the lack of sandy soil in Iowa, Boone County region, the sandy-loam soil selected had lower clay content and a high percent of the sand content. The sandy-loam soil texture consisted of 67\% sand, 25\% silt, and 8\% clay; the loam had 49\% sand, 34\% silt, and 17\% clay. Accordingly, the sandy-loam and loam soils were classified as non-saline due to low electrical conductivity values of 0.179 dS m\(^{-1}\) and 0.505 dS m\(^{-1}\), respectively (Brown, 1998). The assumption was that the two soils represent the average soil characteristics where they were collected with less organic matter and undulated soils. The sandy-loam and loam organic matter measured were 2.64\% and 4.74\% , respectively. The soil bulk density and soil moisture were measured according to the ASTM D7263 and ASTM D2216 standards (ASTM, 2010, 2018); thereby, determining that the dry bulk density of sandy-loam and loam were 1.41 g cm\(^{-3}\) and 1.47 g cm\(^{-3}\). The soils information is presented in Table 5.1. The two soils were transferred into the soil containers (soil-bins) measuring 152.4 long \(\times\) 29.21 wide \(\times\) 25.40 deep cm. Figure 5.1 represents the experimental layout of soils in the bin and seeds placed at different depths and spacing. The soil bins were filled with soils to a depth of 20.32 cm.

<table>
<thead>
<tr>
<th>Textural class</th>
<th>Sand (%)</th>
<th>Silt (%)</th>
<th>Clay (%)</th>
<th>BD (g cm(^{-3}))</th>
<th>EC (dS m(^{-1}))</th>
<th>OM (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loam</td>
<td>49</td>
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<td>17</td>
<td>1.47</td>
<td>0.51</td>
<td>4.47</td>
</tr>
<tr>
<td>Sandy-loam</td>
<td>67</td>
<td>25</td>
<td>8</td>
<td>1.41</td>
<td>0.18</td>
<td>2.64</td>
</tr>
</tbody>
</table>

BD - Bulk density (g cm\(^{-3}\)), EC - Electrical Conductivity (dS m\(^{-1}\)), OM - Organic matter (%)
5.2.2 Field-corn seeds

The field-corn seeds used in the study were primarily chosen since there are commonly used in precision seeding delivery equipment. The Pioneer P0339AMXT Precision Design Round (PDR) field-corn (hereafter termed CS) was used. The CS had an average moisture content of 10.1% (oven drying at 135°C for 2 hours, AOAC 930.15). The physical dimensions (Length, Width, and Height) were measured from a 30 sample size using a Vernier caliper of the accuracy of 0.1 cm. The average dimensions were 1.15 cm, 0.73 cm, and 0.55 cm, with standard deviation of 0.06 cm, 0.03 cm, and 0.05 cm, respectively. A total of six CS were buried in a row at planting depths of 3.81 cm (1.5 in.), 6.35 cm (2.5 in.), and 8.89 cm (3.5 in.). The first three CS were spaced every 25.4 cm (10 in.), equivalent to a corn population of 52000 plants per hectare (21000 plants per acre) at 76.2 cm row spacing. The last three in the row spaced every 15.24 cm (6 in.), accruing to a corn population of 52000 plants per hectare (21000 plants per acre) at 76.2 cm row spacing, respectively (Figure 5.1a). The CS were buried in sandy-loam and loam soils such as that in (Figure 5.1a & 5.1b). The seed orientation in the soils did not matter because of their small size.

Figure 5.1 Experimental setup (a) CS inside soil box section where seeds were buried at different planting depths and spacing in a single row, (b) top view of a single soil type in a box section, (c) parallel orientation of the GPR antenna.
Subsoil inclusions (i.e., soil water, saline concentration, texture and other unconsolidated and consolidated particles) can be extremely difficult to distinguish from other dielectric targets since soils are dielectric with different constituents. Prior to using real CS, conductive (stainless steel) targets were used to mark how the hyperbolic responses would appear in a B-scan at different depths (see, Figure 5.2). The stainless steel targets had the same dimensions as the real CS and were placed at the exact depths at which CS were to be placed. Figure 5.2 shows the hyperbolic trend at the local position of each transect. Therefore, in the case of CS, the hyperbolic response patterns would be expected to mimic the depiction in Figure 5.2. However, the dielectric properties of the stainless steel and that of the CS are markedly different. Accordingly, the hyperbolic responses from CS could be less distinct with lower intensity when compared to Figure 5.2.

![Figure 5.2 Raw B-scan of stainless steel targets at the exact location of the CS in the sandy-loam soil. The red arrows show the exact positions of the steel targets](image)

**Figure 5.2** Raw B-scan of stainless steel targets at the exact location of the CS in the sandy-loam soil. The red arrows show the exact positions of the steel targets

### 5.2.3 Ground Penetrating Radar (GPR)

The experimental data used in this investigative research was collected using a portable Subsurface Interface Radar (SIR) 3000 GPR from Geophysical Survey Systems, Inc. with an antenna frequency of 2.6 GHz (model 52600, GSSI). The 2.6 GHz short electromagnetic wave pulses exploit subsurface properties to detect buried reflectors or targets. The dielectric discontinuity influences reflections and have the potential to yield intermittent scattering pattern of waves which could result in noisy data. The reflected GPR waves consist of the air-soil response amplitude or electric
field strength (V m\(^{-1}\)), time of flight (ns), and target response amplitude. The GPR is application specific, and the most essential feature of the GPR is the resolution. The GPR antenna has two categories of resolution, namely the vertical and horizontal resolution (Pérez-Gracia et al., 2008; Rial et al., 2009). Horizontal resolution signifies a minimum distance that could result in two targets being detected separately. That depends upon specified trace number per distance (m or ft), the size of the wave cone, accessed depth to the target, and the spacing between targets. The vertical resolution depends on the antenna center frequency and propagating wave velocity which precludes two or more events from overlapping (Prego et al., 2017). The vertical and horizontal resolutions are defined in Equation 5.1 & 5.2, respectively. Based on the two equations, the center frequency has the utmost influence on the GPR resolution parameters. Therefore, a compromise between the depth of penetration and spatial resolution has to be considered depending on the objective of the survey.

\[
T_m = \frac{c}{4 \times f \times \sqrt{\epsilon}} \quad (5.1)
\]

\[
A = \frac{\lambda}{4} + \frac{D}{\sqrt{\epsilon} + 1} \quad (5.2)
\]

where \(T_m\) - minimum thickness resolved (cm), \(c\) - the speed of light (cm/s), \(f\) - antenna frequency (GHz), \(\epsilon\) - relative dielectric permittivity, \(A\) - radius of the footprint (cm), \(\lambda\) - antenna frequency wavelength (cm), and \(D\) - depth (cm) between the antenna and target. These two antenna resolution defines the ability of the GPR to image and display finer details of an object in a discernible way.

### 5.2.4 Data collection

The data was collected using a linearly polarized common-offset antenna (the electric field was polarized parallel along the survey direction, as shown in Figure 5.1c. CS are small. Therefore their orientation in the soil was insignificant. The antenna could not be aligned perpendicular along the long axis of the CS to assure the diffraction of waves to generate a hyperbolic response. However, the detection was dependent on the two resolution parameters. The primary treatments in the soil bins were the two soil types, three soil VMC groups, two CS spacing, and three CS depths, and, and the Pioneer P0339AMXT PDR variety as the response variable (\(2 \times 3 \times 3 \times 2 = 36\) combinations). Non-saline sandy-loam and loam soils were used, and the CS were buried as shown
in Figure 5.1a. Five replicates for each of these treatments were collected using the 2.6 GHz GPR antenna. A total of 180 experimental test runs \((5 \text{ replications} \times 36 \text{ combinations} = 180 \text{ runs})\) were performed using 1080 CS \((180 \text{ runs} \times 6 \text{ CS} = 1080 \text{ CS})\) (1079 spacing), nominally. The CS were used once and discarded after each test. Radargrams of the five replicates were collected along a row from the widely spaced CS of 25.4 cm (10 in.) to a much narrower spacing of 15.24 cm (6 in.) as shown in Figure 5.1a. The 2.6 GHz antenna was mounted on a cart which had an encoder to measure accurately spatial distance or position. The cart rail was designed to be placed atop soil to prevent the cartwheels from plowing into the soils, hence causing drag. Moreover, system control parameters were adjusted to suit a soil type in the soil bins. The configured system control settings for the SIR-3000 unit for the most effective data acquisition in the soil bins and detection of corn seeds are presented in Table 5.2. The VMC measurements were divided into three groups, dry, intermediate, and moist soil (Table 5.3). The soil VMC’s were measured in three separate occasions with an interval of atleast ten days between VMC groups. The oven-dry method was used to measure the soil VMCs according to the ASTM D2216 standards.

Table 5.2  Configured system control parameters for the SIR-3000 unit

<table>
<thead>
<tr>
<th>Parameter description</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Antenna model</td>
<td>52600S</td>
</tr>
<tr>
<td>Samples per scan</td>
<td>1024</td>
</tr>
<tr>
<td>Scans per foot</td>
<td>100</td>
</tr>
<tr>
<td>Scans</td>
<td>60</td>
</tr>
<tr>
<td>Bits per sample</td>
<td>16</td>
</tr>
<tr>
<td>Number of gains</td>
<td>7</td>
</tr>
<tr>
<td>Pulse duration (ns)</td>
<td>0.4</td>
</tr>
<tr>
<td>Time window (ns)</td>
<td>2.5 to 5.0</td>
</tr>
</tbody>
</table>

Table 5.3  Classification of soil VMC groups

<table>
<thead>
<tr>
<th>VMC group</th>
<th>VMC (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dry</td>
<td>0 &lt; VMC &lt; 5</td>
</tr>
<tr>
<td>Intermediate</td>
<td>5 &gt; VMC &lt; 13</td>
</tr>
<tr>
<td>Moist</td>
<td>13 &gt; VMC &lt; 20</td>
</tr>
</tbody>
</table>
The CS spacing and planting depth were measured to determine the efficacy, consistency, and accuracy of the GPR in mapping CS buried in sandy-loam and loam soils, at different soil VMCs. The dry group had soil VMC’s ranging from 2.31% to 2.95% for the sandy-loam and 2.47% to 2.96% for the loam. The intermediate group had soil VMC’s ranging from 10.37% to 11.34% for the sandy-loam and 10.22% to 13.28% for the loam. Lastly, the moist group ranged from 15.03% to 17.07% for the sandy-loam and 16.03% to 18.80% for the loam soils. The parameters in Table 5.2 were kept constant for the entire data collection; however, the calibrated wave velocity or total wave time to traverse the soil was variable according to soil conditions. On the other hand, the seven time-dependent antenna gains were variable depending on soil type conditions. For instance, for a soil type of specific VMC group the time-dependent gain points were kept constant. However, migrating to a different experimental unit the time-dependent gains were changed accordingly to suit soil bin conditions. The variation of the time-dependent gain points were variable with respect to the depth.

5.2.5 Application of image processing for discrimination of CS responses

GPR data is highly susceptible to noise resulting from internal soil inhomogeneities (varying and contrasting constitutive properties as influenced by soil moisture contents, composition, and bulk density). The contrasting constitutive properties may cause increased absorptions and intermittent reflections of the GPR waves within the soil. The phenomenon may play an essential role in concealing the actual response from the CS targets. The radargram quality may be compromised. The feature of interest in the radargrams were the CS hyperbolic responses, which in this research were deficiently weak, tainted by noise, and, in some soil conditions, they were not visible. The intuitive analysis of the radargrams was not possible due to the complexity of the data. The Fast Discrete Curvelet Transform (FDCT), an image processing technique, was applied accordingly to discriminate CS from surrounding noise improving the signal-to-noise ratio. Discrimination was an essential aspect in CS detection. The process of discriminating and identifying CS hyperbolic responses was performed in a stepwise approach to suppress noise responses and simultaneously to enhance SNR of the subtle hyperbolic responses in the radargrams. Most importantly being heedful not to discard essential information within the image. The discrimination of CS was achieved by varying the scales and angles of the FDCT-Wrap method to attain the desired image quality (i.e., showing defined hyperbolas). The manipulation of the FDCT scales and angles were dependent on the input image.
The horizontal features or antenna ringing, and clutter responses were reduced on the radargrams, and the FDCT was capable of emphasizing the edges or curves of the hyperbolic seed responses. However, not only the edges from CS responses were amplified with this technique. The unfiltered ridges or horizontal bands were also magnified creating a complex problem to identify the target response. For instance, to identify the corn seed responses from several hyperbolic responses, as shown in Figure 5.6c, a match and select algorithm was created (discussed later).

### 5.2.5.1 How the FDCT works

The FDCT-Wrap algorithm is suited to images with edges or curves, whereby the coefficients are calculated to enhance curves in an image. For example, an input to the FDCT-Wrap is a Cartesian array \( f(m, n) \) of a 2D image with \( M \) by \( N \) dimensions. The array is then decomposed to digital Curvelet coefficients computed as shown in Equation 5.3. The FDCT digital coefficients are indexed by the scale \( j \), orientation \( l \), and spatial location parameters \( k_1 \) and \( k_2 \) (AlZubi et al., 2011). From the estimated coefficients, the FDCT-Wrap selects Fourier samples for the reconstruction of the image and only the largest coefficients are used while small coefficients are discarded (set to zero). The small coefficients are subjugated by noise, therefore, unused in the reconstruction of the image.

\[
C^D(j, l, k_1, k_2) = \sum_{0 \leq m \leq M} \sum_{0 \leq n \leq N} f[m, n] \phi^D_{(j, l, k_1, k_2)}[m, n] 
\]

where \( \phi^D_{(j, l, k_1, k_2)} \) is the digital Curvelet waveform, and \( D \) is for the digital. The matGPR is a software package that is used in MATLAB. The FDCT-Wrap technique is a built-in function in matGPR developed by Tzanis (, 2013, 2015).

### 5.2.6 Corn seed depth

Corn seed planting depths were estimated using Equation 5.4

\[
D_e = \frac{ct}{2/\epsilon} 
\]

where \( D_e \) is the estimated CS depth (m), \( c \) is the speed of light (m ns\(^{-1} \)), \( t \) is the two-way time to target (ns), and \( \epsilon \) is the relative dielectric permittivity. The matGPR has the capability to provide the CS coordinates \((x, y)\) from the 2D image and an index representing the pixel intensity (apex amplitude). The \( x \) and \( y \) represent the spatial distance and total two-way travel time (depth),
respectively. The relative dielectric permittivity was calculated using the Topp’s dielectric and soil mixing models (Topp et al., 1980; Peplinski et al., 1995). The two dielectric models have displayed substantial fidelity in predicting soil dielectric permittivity. It was for that reason their usage in this research important because the effects arising from treatment factors would be factored in the models to minimize error in predicting the soil dielectric permittivity ($\epsilon$). The $\epsilon$ parameter was essential for correcting and predicting the GPR wave velocity which was critical for CS depth estimation.

A third model was introduced to calculate the dielectric permittivity of the two soils. The dielectric model was developed as a function of the dielectric permittivity from the soil mixing ($M$) and Topp’s dielectric ($T$) models as shown in Equation 5.5. The new dielectric prediction model was referred to as the Topp-Mixing (TM) model. The model purpose was to minimize and optimize planting depth measurement error (ME) by combining the effects of the treatment factors from $M$, and $T$. The predictor variables $M$, and $T$ are estimated from measured soil data. Equation 5.6 represent a linear regression model with coefficients predicted as explained below:

$$\epsilon = \epsilon_{TM} = f(M, T)$$

(5.5)

$$\epsilon_{TM} = \alpha + \beta X_i + \epsilon_i = \beta_0 + \beta_1 M_i + \beta_2 T_i + \epsilon_i$$

(5.6)

where $\epsilon_{TM}$ is the TM dielectric permittivity, $\hat{\beta}_i$ model coefficients, $\epsilon_i$ is the model error. The expected mean model error is zero ($\epsilon_i = 0$).

The measured data was randomized and split into training and testing sets. The training set had 70% of the data points while 30% was reserved for testing. From the training data we predicted the linear regression coefficients $\hat{\beta}_i$. The algorithm that predicts the $\hat{\beta}_i$ search for the global minimum values of the training data to minimize the statistical difference in the predicted and actual depths. The $\hat{\beta}_i$’s were used to estimate the dielectric permittivity $\epsilon_{TM}$ from test data. The accuracy of the predicting coefficients were determined by comparing the training and testing adjusted sum of squared error (SSE), estimated as shown in Equation 5.7:

$$SSE = \sum_{i=1}^{n} (y_i - \hat{y}_i)^2 = \sum_{i=1}^{n} (y_i - D_e)^2$$

(5.7)

where $y_i$ is the actual depth measurement, $\hat{y}_i$ is the predicted depth measurement with leave-one-out, n sample size of the training data and $i$ position of an element in the training data. The
\( \hat{\beta}_i \) values would be estimated in such a way that they minimize the SSE parameter. To achieve the latter, the cost function \( J \) was used as shown in Equation 5.8:

\[
\frac{\partial J}{\partial \hat{\beta}_{\text{min}}} = \frac{\partial \text{SSE}}{\partial \beta}
\]  

### 5.2.7 Data analysis methods

The match and select algorithm was developed to match the measured seed spacing to the known spacing values. A parameter termed Coefficient of Precision (CP3) was used. The CP3 parameter assesses the seed spacing uniformity by accounting for variation spacing in a row. The parameter has been reported to have different tolerances depending on the planter seeding delivery and correlated to the forward speed and field slope (Searle et al., 2008; Kocher et al., 2011). The greater the percentage spacing (e.g., > 70\%) would be considered good, while the others e.g., < 70\% would have more variations in spacing or inconsistent. Therefore, the CP3 is the percentage of seed spacing that falls within the ± 1.5 cm of the theoretical spacing. The tolerance adopted for our laboratory experiment was ± 3 cm (1.2 in.) of the CS spacing. The idea was during CS burial using levelers seeds may have been pushed shifted from their original positions when hand sowing and leveling up the soils. Also, for the assessment of the 2.6 GHz antenna effectiveness and accuracy to measure CS depth, the coefficient of planting depth accuracy (CPDA) was used. For our experiment ± 0.005 cm. Lower percentage values of the CPDA would represent the lowest minimal deviation from the recommended theoretical planting depths.

### 5.3 Results

The radargrams in Figure 5.3 are presented as measured, from sandy-loam and loam soils at the three VMC groups. The data consisted of 500 sample \( \times \) 1024 traces with a sample rate of \( \sim 0.0024 \) ns (time window of 2.5 ns) and trace spacing of 0.3048 cm (section length of 152.4 cm). The most important feature in the images were the signatures of the buried CS. In Figure 5.3, the CS hyperbolic signatures were not all visible on the radargrams due to clutter or soil inhomogeneity. The data was profoundly noisy. As observed on the radargrams, there are dominant antenna ringing (horizontal features), and angled edge features that appear to be shadowing important CS details or obscuring the CS hyperbolic responses.
Figure 5.3  GPR raw data of buried CS in sandy-loam, (a) represent radargrams from dry, (b) intermediate, and (c) moist group. The red arrows show the positions where CS should be in the image. The yellow arrows show the identified CS with faded hyperbolas. The white arrows show positions of the undetected CS (no hyperboles) or undiscernible responses or the responses that are either from CS or artefacts within the soil.

It is evidently clear in Figure 5.3 & 5.4 that CS detection is challenging in all soil conditions using the 2.6 GHz GPR. In the dry group (Figure 5.3a & 5.4a), the two soils surrounding the CS were deficient in moisture contents compared to the CS. This phenomenon created a substantial dielectric contrast between the soil and CS. Because of the dielectric contrast in moisture, the CS were successfully located at shallow depths and spacing. Not all CS were detected, and some seeds showed extremely faded hyperbolic responses and others that were not substantively perceptible. Also, observed in the dry category was the incapability of the antenna to map the CS that were buried deeper in the soil bins. Near-surface CS (3.81 cm) were sub-par distinguished from the soil matrix compared to no response from the CS that were buried deeper (8.89 cm). For all the
replicates, deeper CS were hardly visible, as shown in Figure 5.3a & 5.4a. For the figures with no yellow arrows, it was challenging to identify CS visually. The radargrams showed different total two-way travel times depending on the soil VMC group. For instance, the drier soils showed less two-way travel time compared to wet soils.

In the intermediate (Figure 5.3b & 5.4b), and moist groups (Figure 5.3c & 5.4c), CS were sparsely detected. The two soil VMC groups were observed to affect the CS detection profoundly. Multiple intermittent reflections at the location and regions around the CS and strong horizontal ringing within the radargrams were observed (noise variation due to artifacts, soil moisture). It was difficult to visualize where the targets were within the radargrams. For the intermediate group, it made sense when CS were not detected - the sandy-loam and loam VMC’s were close to the CS moisture. Therefore, little or no contrasting interfacial properties existed between the soils and
CS. No reflection implied that the 2.6 GHz antenna was seeing a single layer along the GPR wave propagation path.

However, it could have made sense in the moist group to have detected CS because of the disparity between the soil and CS moisture. The moist soils had higher VMC which confounded the detection of the CS. The confounding effect had reduced the antenna resolution (see vertical and horizontal resolution) to map buried CS in some specific (higher moisture conditions) spatial domain characterized by sparse mapping Figure 5.3b, & 5.3c, and 5.4b, & 5.4c). Nonetheless, the Fast Discrete Curvelet Transform image processing technique was used to denoise and discriminate CS from artifacts, and clutter scattering.

5.3.1 GPR image processing using Fast Discrete Curvelet Transform

Collected radargrams predominantly convey the positions of the buried CS. For some of the radargrams the CS positions were not visible within the image because the images were heavily subjugated by noise, particularly in intermediate and moist VMC groups, see Figure 5.3b, & 5.3c, and 5.4b, & 5.4c). Therefore, image enhancement was necessary for the CS position accentuation, to enable the GPR data analysis and interpretation. Firstly, we explored the concept referred to as the background subtraction (BKG). For the BKG, a difference of the CS and averaged target-free A-scan was calculated the result is shown in Figure 5.5. Figure 5.5 illustrates an A-scan before and after background subtraction. Accordingly, the BKG was substantially efficient for CS that had partially strong hyperbolic responses, Figure 5.3a (marked with yellow arrow). The parameters such as the amplitude and two-way travel time were extracted from the figure. It was observed Figure 5.5 that the CS amplitude was normalized to the baseline. The estimated CS two-way travel time was 0.59 ns with amplitude of 2216 after BKG. After zero-correction time was performed, the buried CS depth was predicted to be 3.68, 4.78, and 4.85 cm from the Topp-Mixing, soil mixing, and Topp’s dielectric models, respectively.

The BKG would have been suitable for all CS buried at different depths in the soil-bin and with discernible hyperbolas. The BKG method, however, is point-based and localized. The disadvantage with this point-based technique is that the image cannot be reconstructed, and the selected window width does not always work on targets that are buried at different depths having deficient amplitude intensity.
The results have shown that (even though soils were clean) there were high soil inhomogeneities that contaminated the data and perhaps distorted CS responses. The lack of the soil uniformity resulted in the BKG process not being used.

The FDCT-Wrap technique was capable of subduing noisy elements and enhance the hyperbolic responses through suppression of ringing noises, and enhancement of the curve edges from the Curvelet waveform coefficients. The estimated Curvelet waveform coefficients can only work to a certain extent to denoise and enhance the curve singularities on the B-scan. For instance, weak hyperbolic responses (Figure 5.6a) were successfully improved by the Curvelet waveform coefficients (Figure 5.6b). Even after applying the FDCT-Wrap technique, in some radargrams CS responses were not visible. However, due to the complexity of the radargram, the technique was capable of improving the edges or curves that were thought to have come from artifacts or constructive interference’s (ghost hyperboles). Coincidentally, some of these strong edge response (artifact responses) occurred at the locations where the CS should have been and some everywhere else within the picture as shown in Figure 5.6c.
Figure 5.6 Radargrams collected from the sandy-loam soil: (a) raw radargram from dry VMC group with one target visible, (b) processed radargram from dry VMC group with few CS targets visible, and (c) processed radargram from intermediate VMC group with mostly strong edges from artifacts.

Extracting the important parameter (two-way travel time) from Figure 5.6c was complicated. Consequently, for these kind of data (Fig. 5.6c) we proposed that (1) for any surrounding hyperbolic response that was proximal to temporal spacing and depth positions of the CS within the image, their parameters were extracted and (2) a matching and selecting algorithm was developed to match the temporal spacing and depth positions of the hyperbolic response to the actual spacing and depth as discussed in the methodology section. The matching and selecting algorithm used the CP3 and CPDA values of $\pm 3$ cm and $\pm 1$ cm, respectively. The corresponding planting depths computed as function of the three dielectric models and the two-way travel times are shown in Appendix B Table ??. (Note: Data in Table ?? represent measured or sampled data from sandy loam and
loam soils at different soil volumetric moisture contents). The percentage CP3 values for the CS spaced 25.4 cm apart were 28%, 24%, and 26% in dry, intermediate, moist groups, respectively were detected. For the CS spaced 15.24 cm the CP3 values were 15%, 7%, and 20% in dry, intermediate, moist groups, respectively were detected (Table 5.5). These numbers are typical low for CP3. The disparity in the spacing precision was primarily from inability of the 2.6 GHz GPR antenna to detect seeds in sandy-loam and loam soils in different moisture groups. The CS that were detected out of the total CS used in the experiment replications were extremely low as indicated by low CP3 percentages.

5.3.2 Statistical analysis

5.3.2.1 Estimation of the Topp-Mixing model

From the experimental data, the following linear regression model coefficients were estimated: $\beta_0 = 4.90, \beta_1 = 0.64, \text{and } \beta_2 = -0.48$ with p-values of $p_0 = 1.58 \times 10^{-10}, p_1 = 0.19, \text{and } p_2 = 0.39$. The predicted TM model is given in Equation 5.9:

$$\epsilon_{TM} = 4.90 + 0.64 M_i - 0.48 T_i \quad (5.9)$$

The most crucial factor in mapping CS was to accurately estimate the CS spacing and planting depths using GPR. The measured spacing and depths (Table 5.4) were compared to the known CS spacing and depths by determining the sums of squared error (SSE) statistics. The predicted SSE statistics for the Top-Mixing, soil mixing, and Topp’s dielectric models were 17.93, 30.53, and 31.82, respectively. The Topp-Mixing model had the lowest SSE statistics which showed that the predictive ability of the model was efficient in estimating the dielectric permittivity of the soil. In Table 5.4 we show average measured spacing and depth measurements and standard deviations associated with each measurement model. The dielectric models are provided in Appendix A Table A.1.
Table 5.4  Descriptive statistics comparison of GPR estimated CS depth in dry sandy-loam and
loam soils according to the CS spacing

<table>
<thead>
<tr>
<th>Dielectric model</th>
<th>Actual depth</th>
<th>15.24 CS spacing</th>
<th>25.40 CS spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil mixing</td>
<td>3.81</td>
<td>4.32 (1.04)</td>
<td>4.57 (1.09)</td>
</tr>
<tr>
<td></td>
<td>6.35</td>
<td>6.10 (1.52)</td>
<td>7.11 (1.35)</td>
</tr>
<tr>
<td></td>
<td>8.89</td>
<td>8.13 (1.35)</td>
<td>8.38 (1.17)</td>
</tr>
<tr>
<td>Topp’s dielectric</td>
<td>3.81</td>
<td>4.57 (1.12)</td>
<td>4.83 (1.17)</td>
</tr>
<tr>
<td></td>
<td>6.35</td>
<td>6.10 (1.52)</td>
<td>7.37 (1.40)</td>
</tr>
<tr>
<td></td>
<td>8.89</td>
<td>8.38 (1.14)</td>
<td>8.64 (1.17)</td>
</tr>
<tr>
<td>Topp-Mixing dielectric</td>
<td>3.81</td>
<td>4.32 (0.69)</td>
<td>4.57 (0.99)</td>
</tr>
<tr>
<td></td>
<td>6.35</td>
<td>5.84 (0.94)</td>
<td>6.60 (1.12)</td>
</tr>
<tr>
<td></td>
<td>8.89</td>
<td>7.87 (0.66)</td>
<td>8.64 (0.94)</td>
</tr>
</tbody>
</table>

All measurements are in centimeters (cm)

Table 5.5  The percentage of seeds detected within the CP3 value from the 2.6 GHz antenna per
soil VMC group

<table>
<thead>
<tr>
<th>Corn population</th>
<th>Nominal spacing (cm)</th>
<th>Dry (%)</th>
<th>Intermediate (%)</th>
<th>Moist (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>86000</td>
<td>15.24</td>
<td>15.00</td>
<td>7.00</td>
<td>20.00</td>
</tr>
<tr>
<td>52000</td>
<td>25.40</td>
<td>28.00</td>
<td>24.00</td>
<td>26.00</td>
</tr>
</tbody>
</table>

The hypothesis for using the three dielectric predicting models was: each treatment factor used
in the estimation of the dielectric permittivity would correct for the GPR wave velocity, which can
then be used to calculate the planting depth. Therefore, any treatment factor or interaction of
treatment factors that have p < 0.05 would be significant. That would mean the treatment factors
affected the estimated planting depth measurement error. The VMC group was significant for the
TM and Topp’s dielectric models, (p values < 0.0001, Table 5.6). Since the Topp’s dielectric model
uses the VMC to predict the permittivity, it should have accounted for the VMC group effect to
correct for the wave velocity. Instead, the model has over-corrected for the wave velocity from the
soil type. The soil mixing model has performed well (p values > 0.05) in reducing the effect of all
treatment factors in the wave velocity and planting depth measurement error estimation. Since an
opposite effect was observed in the Topp’s dielectric model (Table 5.6), it may have contributed to
the significance of the VMC group in the TM model. With an over correction of the soil type (p
= 0.9129) and interaction between the soil type and VMC group (p = 0.510), the TM model was
better at estimating the planting depth measurement error. The TM model had a CPDA value of
8.37% compared to 21.56% and 22.01% of the Topp’s dielectric and soil mixing models, respectively.
Table 5.6 Analysis of variance on the effect of each treatment factor in the prediction of CS planting depth error based on the three dielectric models.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Topp-Mixing model (F Ratio) (Prob &gt; F)</th>
<th>Soil mixing model (F Ratio) (Prob &gt; F)</th>
<th>Topp’s model (F Ratio) (Prob &gt; F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil</td>
<td>1</td>
<td>0.012 (0.9129)</td>
<td>0.231 (0.6319)</td>
<td>0.027 (0.8710)</td>
</tr>
<tr>
<td>VMC group</td>
<td>2</td>
<td>28.011 (0.9032)</td>
<td>2.614 (&lt; 0.0782)</td>
<td>10.532 (&lt; 0.0001)</td>
</tr>
<tr>
<td>Soil : VMC group</td>
<td>2</td>
<td>0.677 (0.510)</td>
<td>0.189 (0.8279)</td>
<td>0.969 (0.3829)</td>
</tr>
<tr>
<td>Error</td>
<td>5</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Table 5.7 Least Square Means with standard error for the CPDA parameter for all combination of the treatment factors: soil, VMC group and the interaction of the soils and VMC groups.

<table>
<thead>
<tr>
<th>CS depth estimation model (%)</th>
<th>Least Square Means</th>
<th>Standard error</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topp-Mixing</td>
<td>8.37</td>
<td>2.59</td>
</tr>
<tr>
<td>Topp’s dielectric</td>
<td>21.56</td>
<td>3.37</td>
</tr>
<tr>
<td>Soil mixing</td>
<td>22.01</td>
<td>3.14</td>
</tr>
</tbody>
</table>

(Table 5.7). Though the soil mixing model shows to have performed well (Table 5.6), the marginal means indicate that it had the highest CPDA (Table 5.7). In addition, the Topp-Mixing model had the lowest standard error compared to the other models (Table 5.7). Thus, the Topp-Mixing had proven to be effective in minimizing the planting depth measurement error.

5.3.3 Discussion

The purpose of this study was to introduce a new method of estimating CS planting depth and spacing in a non-destructive manner. Measuring CS spacing, and depths non-destructively is vital and would prevent utilization of the destructive method (conventional method - dig and search). Non-destructive measurements may reduce error in measurements and repeatability in measurements would be possible compared to destructive method. A complete randomized design was implemented. The utility of 2.6 GHz GPR antenna to detect and quantify CS planting depth was evaluated in soil bins under controlled laboratory conditions and met with infrequent success. The radargrams acquired were meager with prevalent noise. The major finding of our study were that the dry soils and water contents of the buried CS were critical in the detection. Though moisture confounds GPR
wave detection, it is evidently shown in this study that CS moisture content played an integral part in GPR application for locating buried CS in drier soils (Figure 5.6a). For subsurface detection a sufficient gradient between soil and roots has to exist (Bain et al., 2017), which was observed to be the case in this particular study for CS. Furthermore, results suggest that GPR at the right frequency and appropriate soil VMC, it can be a tool for quantifying seeds in future research.

Although the radar waves can penetrate the soil beyond 17.78 cm in the soil bins at intermediate and moist groups, CS were not detected. The dispersion of the wave within the soil may have been great to obscure the CS responses. One thing to note was the CS used in the study were small (PDR size) and their orientation layout in the soil bins did not influence detection. In most B-scans CS response features were nonexistent or not clearly pronounced which complicated the extraction process in processed soils. Though the soils were processed a number of limiting factors may have hid or distorted CS responses. During data processing the following points were made as probable limiting factors for the GPR detection: (1) effects from the antenna frequency whereby multiple intermittent scattering were prevalent; (2) the soil physical properties that governed GPR wave velocity, attenuation, absorption; 3) the dielectric contrast between the soil and the CS determining the strength of the CS response and; 4) the CS size and the shallow depths. The ineffectiveness of the 2.6 GHz GPR was correlated with higher soil VMC and somewhat the CS size and shallow depths. The prevalence of multiple intermittent scattering at higher soil VMC was overwhelming hence the radargrams quality were sub-par with no discernible CS responses.

The three models were compared based on the CPDA value. The dielectric permittivity estimated using the TM, Topp's dielectric, and soil mixing models were in some cases underestimating or overestimating the planting depth (Table 5.4) which may have been influenced by several covariate factors. The statistical analysis indicates the significance between the soil and VMC groups interaction. This may mean the amount of water in the soil was critical in the detection of seeds (as explained above). The boxplots in Figure 5.7, show the distribution of the predicted planting depths based on the three predictive models. The TM model displays a narrow distribution of the three depths measured with the exception of the outliers at the 6.35 cm. The narrow distribution could mean most of the predicted depth measurements were close to the known depths (3.81 cm, 6.35 cm, and 8.89 cm). Note that the TM model CPDA value was determined to be low (8.37%), which improves accuracy for shallow buried targets. However, deeper targets would have larger errors in measurements. The soil mixing and Topp dielectric models mean measurements were predicted
Figure 5.7  Boxplots for temporal CS depths estimated using three dielectric permittivity models. Planting depth: shallow, moderate, and deep correspond to 3.81 cm, 6.35 cm, and 8.89 cm, respectively. (Topp-Mixing = Topp-Mixing model, SoilMixing = Soil mixing model and Topps = Topp’s dielectric model). The data presented is from the detected corn seeds only.

close to the known depths, but, the distribution of the measured depths was spread out with higher standard deviations, Table 5.7 and Figure 5.7.

The objective of this research was successfully met when soils were dry, and the accuracy of depth measurement was determined best using TM model. More research needs to be conducted with different sets of GPR frequencies preferably higher than the 2.6 GHz or a combination of other sensing mechanisms employed in tandem to increase chances of mapping CS in a variety of soil conditions. The preliminary results presented in this study showed a positive development towards the attainment of a nondestructive technique to map CS spacing and planting depth. We also recommend further studies with different CS variety and sizes (i.e., precision design flats, medium flats, and large rounds), and natural sandy soils to evaluate the GPR and progression of this work.
5.4 Conclusion

Experiments were performed to detect corn seeds using 2.6 GHz Ground Penetrating Radar (GPR) in sandy-loam and loam soils having different conditions. The corn seeds spacing and depth were quantified with mixed success. The corn seeds were buried at three different depths and two different spacing. The soil VMC were divided into dry, intermediate, and moist groups of which were within 2.31\% to 17.07\% for the sandy-loam and 2.50\% to 18.80\%, for the loam. Pioneer P0339AMXT PDR (1459 kernels/lb.) corn variety was used with the determined moisture of 10.1\% (d.b.). The primary objective was met in this study. In conclusion, the main findings of this investigative study were: (i) the developed Topp-Mixing model from the experimental data yielded best CPDA compared to the soil mixing and Topps dielectric model. The models, however, had instances where they underestimated or overestimated planting depth, and (ii) the preliminary results in this research indicates that the 2.6 GHz GPR antenna can quantify corn seeds planting depth at an accuracy of 8.37\% and spacing. The GPR system failed to meet the acceptable CP3 percentage. (iii) The corn seeds were mostly detected in drier soils (dry moisture group). (iv) Mostly shallow corn were detected. However, more research is needed to enable detection of corn seeds in soil conditions that are typical during planting operations.

References


CHAPTER 6. MANUAL AND GROUND PENETRATING RADAR FIELD MEASUREMENTS OF FIELD-CORN SPACING, PLANTING DEPTH, AND FURROW FEATURE IDENTIFICATION

A paper to be submitted in the Journal of Precision Agriculture

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Abstract

The objective of this study was to investigate the utility of a 2.6 GHz GPR system to measure seed spacing and planting depth in a closed furrow and identify features that could potentially represent the furrow path. The experimental design had four treatments: two downforce pressures, three population and planting depth, and two plots. The downforces significantly affected the planting depths and variability. The planting depth variability was more than the nominal resolution of the planter. The effect of the two downforce pressure variances were detected using the 2.6 GHz GPR. Random hyperbolic features were observed across radargrams. The hyperbolic features were inconsistent with the seed depth and it was challenging to identify individual corn seeds. There were horizontal features that were consistent and had similar two-way travel times to the bands observed in parallel and perpendicular radargrams. If the two-way travel times were the same, then it is highly likely that the bands in the parallel and perpendicular radargrams are from the same feature. Using the perpendicular to matchup with the parallel A-scans features that could represent the furrow were effectively identified.
6.1 Introduction

Corn must be planted at optimal depths to achieve the goal of increasing yield. In a study conducted by Karayel and Ozmerzi (2008) the effects of depth control components were evaluated, and the components were found to affect the mean seed depth which reduced yield. Molatudi and Mariga (2009) conducted a study in Limpopo, Mankweng, Republic of South Africa (23° 53’ S, 29° 44’ E) and demonstrated that incorrect planting depth has the potential to reduce corn emergence severely. Planting at optimal depth was observed to have emergence peak in a shorter time compared to a deeper depth which took considerably more time (Knappenberger and Koller, 2012).

Poncet et al. (2018) states that nonuniformity in seeding depth leads to crop hierarchy in terms of plant competition for the required resources while uniform depth has been demonstrated to increase corn yield by 4% to 10%. The Poncet et al. (2018) study focused on several field treatment factors to evaluate their effect on seeding depths. In the study, three planting depths and downforces were tested. The tested planter with six-row was found to be inconsistent and failed to maintain the uniform depths in various soil conditions. Therefore, accurate measurement of the seed spacing and depth could be valuable to precision seeding and improvement of precision planter effectiveness.

Recently the more acceptable (easy method compared to method expounded in ISO (1984) method) manner to measure planting depth is to measure seed depth after seedling emergence (DuPont-Pioneer, 2016). The approach allows for planting depth mistakes to be realized after the fact. Literature presented throughout this thesis indicate that several precision planters have been tested and have shown continuous depth inconsistencies. The GPR was tested under several soil conditions, and it was met with mixed success, and frequently failures Mapoka et al. (2018). The primary objective was to extend the use of the 2.6 GHz GPR antenna to measure corn planting depth and identify the closed furrow path features in the field.

6.2 Materials and Methods

6.2.1 Farm site description

The experimental site was in Boone County, Iowa (Latitude 42.021196 N, Longitude 93.773627 W). The plots were flat with substantial clods, dry topsoil and relatively higher soil moisture content just under the dry soil cover, which ranged from 16% to 23%. The plots were separated by a grassed
waterway, as shown by the aerial map in Figure 6.1 (from Google Earth maps). The soil moisture increased slightly approaching the grassed waterway and conversely, decreased slightly towards the plots lateral extremes. The soils in both plots were classified as loam (Table 6.1). The plots were tilled and received a substantial amount of rainfall after tillage, and planting occurred one week after the last rainfall event. The study had four treatments: two manually selected downforces, three different planting depths and corn population, and two field plots (Total combination = $2 \times 3 \times 3 \times 2 = 36$). Temperatures were approximately 29°C (84°F) with a humidity of 45%. There were four replicates collected per treatment.

![Map of the two plots A and B separated by a grassed waterway, courtesy of Google earth image, coordinates (42.021196 N, Longitude 93.773627 W). The arrow shows the direction of travel at seeding.](image)

**Table 6.1** Field soil information used in the study

<table>
<thead>
<tr>
<th>Textural class</th>
<th>(%) Sand</th>
<th>(%) Silt</th>
<th>(%) Clay</th>
<th>BD</th>
<th>EC</th>
<th>OM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Loam</td>
<td>42</td>
<td>37</td>
<td>21</td>
<td>1.10</td>
<td>0.27</td>
<td>4.90</td>
</tr>
</tbody>
</table>

BD - Bulk density (g cm$^{-3}$), EC - Electrical Conductivity (dS m$^{-1}$), OM - Organic matter (%)
The field-corn seed variety used was the Pioneer P8542AMX-NJ02 PDR CON1 coated with AcreMax. The seeds had an average moisture content of 13.2%. A John Deere tractor (*model 8270R*), and precision 12-row planter (*model 1770NT*) were used to plant field-corn seeds. The planter was relatively new with all the seeding delivery components, gauge and pressing wheels in a good state. Two row-unit downforces treatments were used, with a low downforce of 354 N (79.6 lbs) in plot A, and a high downforce of 451 N (101.4 lbs) in plot B (Figure 6.1). The planter depth control levels were set to provide three nominal planting depth settings 3.81 cm (1.5 in), 6.35 cm (2.5 in), and 8.89 cm (3.5 in), based on the planter manual recommended position settings. The three depth settings were set on the first three rows of the planter and repeated across the 12 planter rows. The nominal planting depths were set according to the nominal planter manual recommended positions by adjusting the depth control T-handle lever (Figure 6.2). The three population treatments included, a zero population treatment (*with the planter opening and closing the 12-row furrows without planting corn seeds*), a low population treatment with a target population of 52000 plants ha$^{-1}$ (21000 plants ac$^{-1}$), and nominal spacing of 25.40 cm (10 in), and a high population treatment with a target population of 86000 plants ha$^{-1}$ (35000 plants ac$^{-1}$), and nominal spacing of 15.24 cm (6 in), respectively. The planter row spacing was 76.6 cm (30 in). The tractor speed for all the test runs was 8 km h$^{-1}$.

![Adjusting planter depth](image)

*Figure 6.2* Adjusting the T-handle depth control of the planter to set the depths graduated 0.635 cm.
There were four compaction zones along the tractor tire treads (adjacent to the furrows) and loose soil zones from each side of the tractor, as shown in Figure 6.3. The planting depths layout was set as shown in Figure 6.4. Subsequently, the pattern was repeated for the remaining half of the planter (not shown).

6.2.2 GPR Data collection

The 2.6 GHz, field-portable GPR antenna (developed by GSSI, Salem, NH, USA), was pushed slowly above and parallel to the furrows on zero population and population zones (Figure 6.5). Thus, 36 rows were scanned for each plot accruing to a total of 72 scans. The GPR antenna was
calibrated for seven time-independent gain points (-4, 9, 18, 19, 18, and 18 dB), and the collected radargrams were 16-bit files and the travel or window time was set to 6 ns. The closed furrows with side banks on each side are presented in Figure 6.6a. As a planter was run, it created two side banks on either side of the closed furrow. In addition, B-scans perpendicular to the furrows was collected per 12-row planter pass, as shown in Figure 6.6a & 6.6b. Figure 6.6b presents a single magnified row with all attributes labeled with the antenna direction across. The purpose of the perpendicular B-scan was to evaluate whether the furrow path or bottom, side banks, and or compaction zones (i.e., caused by opening disks and pressing wheels) could be mapped. After the scanning process, soil core samples were collected for, particle analysis, salinity and organic testing (Table 6.1), and soil volumetric moisture content. Soil moisture content was determined through the oven-dry process at a temperature of 105°C for 24 hours. The measured soil properties were important in estimating the soil dielectric permittivity, used for calibrating or correcting for the wave velocity. It was difficult to measure planting depths immediately after planting. Thus, corn planting depth was determined after seedling emergence. The emerged plant was excavated, and depth was measured as shown in Figure 6.7 (DuPont-Pioneer, 2016).
6.2.3 Data processing

The RADAN 7 from Geophysical Survey Systems was used for GPR radargram display, edition, normalization (i.e., zero-time correction) and filtration routines. Applying the smart gain function amplified the edges and horizontal bands (i.e., ringing noise due to clutter) within the B scan. Filtration routines (applying bandpass filter and stacking) suppressed the background features and
reduced several horizontal or parallel bands observed in the radargrams. The parallel bands (Figure 6.14) may have been the effect of tillage practices, furrow or furrow compaction, plane reflection (soil surface, horizons), and/or from antenna reverberations as the wave traversed through the subsurface. The unfiltered parallel bands made it difficult to discern the position of the furrow in the image. Also, due to the absence of obvious periodic hyperbolic responses in a furrow for either population, suggested that the seeds were not detected or lost in the scatter from non-seed targets. Ghost hyperbolic responses were observed in the image, which were easily filtered out at during processing. There were no periodic signals from the scans, which could be clearly identified and conclusively interpreted as a signal response from the seed targets. Therefore, identifying either the positions or spacing of the corn seeds could not be achieved. However, in the perpendicular B-scan, promising features were observed. The furrow ridges/side-banks were identifiable visually and easy to interpret from the radargrams with parabolic or dip responses (as shown in Figure 6.15), although, identifying the furrow bottom remained a challenge.

6.2.4 Feature extraction and furrow identification process

A total of 36 furrows per plot were collected of which 12 rows were of the depth 1.27 cm, 3.81 cm, and 6.35 cm, respectively. The B-scans were collected parallel and perpendicular to the furrows as described above. Therefore, the four furrows per each depth were considered replicates, given that the soils had similar physical properties. From the replicated B-scans, the A-scans were extracted for each depth and plotted against each other to identify features that were similar, with some time shift of the features considered. This process of overlaying all A-scans of one depth in one figure was to evaluate consistency and repeatability of features. Any inconsistencies within the features of similar soil conditions could signify random noise or clutter in the soil. Given the same soil conditions, a feature that is repeatable and consistent within the correct nominal time zone could be used to identify a response feature from the furrow. A perpendicular A-scan of the same furrow was compared with the parallel A-scan to identify a common response feature that could result in the identification of a furrow at the nominal time frame. Thus, a response feature that was identical in the parallel and perpendicular A-scan at the same time frame could hold information about the furrow. The feature extraction performed seeks to find correspondences of the parallel and perpendicular B-scan of the same furrow path. In the B-scan, we have the positive and negative polarities which correspond to the white and black contrast. As commonly seen throughout this thesis, texture-less B-scan images
made identifying targets difficult. The B-scans with greater gradients (time-dependent contrasting features) enabled easy identification of features. The same would apply to furrow identification, where the furrow with significant contrast would be easiest to localize using features.

In the process of feature extraction, the furrow depth features were not known for each individual B-scan, therefore by clustering the A-scan could be crucial for furrow identification. Further, background subtraction was performed. The A-scan from a non-furrow or non-target was used to conclusively decipher the location of the furrow from other repetitive features within the soil, which aided on perhaps solidifying the furrow feature by further filtering out the noisy features. The hypothesis was the feature used to identify the furrow response must not be at the nominal time frame or location of the non-furrow A-scan. The procedure described above was executed for all 72 furrow depths. This methodology was examined as an alternative to measuring field-corn planting depth. A problem that could arise will be to identify the compaction zone along the furrow path as the furrow feature.

6.3 Data Analysis

The precision planter was assessed for field-corn spacing and planting depth measurements based on the CP3 and CPDA parameters. Analysis of variance was performed to determine the effect of the two downforces on the manually measured planting depths. The linear regression model in R was used. The Tukey Honest Significant Difference (HSD) was used to separate the means between all downforces at 5% level of significance. The interpretation and analysis of the GPR data was qualitative.

6.4 Results and Discussion

6.4.1 Manual measurements

6.4.1.1 Planting depth

After seedling emergence, the corn seed spacing, and planting depth were measured. A total of ten measurements ($n = 10$), were taken for each treatment. The corn seed spacing, and planting depth field measurements are shown in Table 6.2 & 6.5, respectively. Table 6.2 shows averaged planting depths and the distribution of data points with respect to the downforces illustrated in
Figure 6.8. The targeted nominal depths were 3.81 cm, 6.35 cm, and 8.89 cm. But, under the field soil conditions, the actual planter setting were 1.27 cm, 3.81 cm, and 6.35 cm which were 2.54 cm off from the nominal depths. At a depth of 1.27 cm, no seedling emergence was observed. The seeds were mostly exposed on the surface.

Table 6.2  Averaged corn seed planting depth measurement with corresponding standard deviations according to seed spacing, and selected row-unit downforce.

<table>
<thead>
<tr>
<th>Downforce &amp; Population</th>
<th>1.27 cm PD</th>
<th>3.81 cm PD</th>
<th>6.35 cm PD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low force &amp; High population</td>
<td>3.12 (0.66)</td>
<td>5.08 (1.12)</td>
<td></td>
</tr>
<tr>
<td>High force &amp; High population</td>
<td>4.04 (0.74)</td>
<td>6.58 (1.32)</td>
<td></td>
</tr>
<tr>
<td>Low force &amp; Low population</td>
<td>3.00 (1.09)</td>
<td>5.26 (1.12)</td>
<td></td>
</tr>
<tr>
<td>High force &amp; Low population</td>
<td>4.14 (0.91)</td>
<td>6.45 (1.30)</td>
<td></td>
</tr>
</tbody>
</table>

PD - planting depth, std - standard deviation

Figure 6.8  Measured planting depth corresponding to the two downforces.

The two plots had constant soil composition, and the moisture was consistent. For both downforce treatments, the standard deviations of the actual depth measurements were greater than the minimum adjustment resolution of 0.635 cm (0.25 in), as shown in Table 6.2. The planter planting
depth control was highly variable and could not control to the theoretical set depth. Thus, suggested that the CPDA was higher than the acceptable and proposed CPDA value for this research. The imprecise depth control may have been caused by several factors which include the soil surface roughness, inadequate planter downforces, and planter speed and acceleration forces. As expected, the variation in planting depth was higher for the low downforce treatment than the high downforce treatment. The ANOVA (Table 6.3) indicates that the mean planting depth measurements were significantly different \( p < 0.0001 \) for the two planting depth treatments.

<table>
<thead>
<tr>
<th>Source</th>
<th>DF</th>
<th>Sum Sq</th>
<th>Mean Sq</th>
<th>F value</th>
<th>Pr(&gt;F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Downforce</td>
<td>3</td>
<td>527.3</td>
<td>175.8</td>
<td>159.1</td>
<td>&lt; 0.0001</td>
</tr>
<tr>
<td>Residuals</td>
<td>316</td>
<td>349.2</td>
<td>1.1</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Tukey HSD also highlights that the resultant planting depths are influenced by the downforces, as illustrated in Table 6.4. Tukey HSD provides the confidence intervals, differences in means and the adjusted p-values of all the compared pairs. The downforce treatment differences were significant for all the pairs as indicated in Table 6.4.

<table>
<thead>
<tr>
<th>Downforce</th>
<th>Difference</th>
<th>Lower CL</th>
<th>Upper CL</th>
<th>P adjusted</th>
</tr>
</thead>
<tbody>
<tr>
<td>High force shallow - High force deep</td>
<td>-2.430625</td>
<td>-2.859867</td>
<td>-2.001363</td>
<td>0</td>
</tr>
<tr>
<td>Low force deep - High force deep</td>
<td>-1.341500</td>
<td>-1.770761</td>
<td>-0.912238</td>
<td>0</td>
</tr>
<tr>
<td>Low force shallow - High force deep</td>
<td>-3.456375</td>
<td>-3.885637</td>
<td>-3.027113</td>
<td>0</td>
</tr>
<tr>
<td>Low force deep - High force shallow</td>
<td>1.089125</td>
<td>0.6598633</td>
<td>1.5183867</td>
<td>0</td>
</tr>
<tr>
<td>Low force shallow - High force shallow</td>
<td>-1.025750</td>
<td>-1.455017</td>
<td>-0.596483</td>
<td>0</td>
</tr>
<tr>
<td>Low force shallow - Low force deep</td>
<td>-2.114875</td>
<td>-2.544137</td>
<td>-1.685613</td>
<td>0</td>
</tr>
</tbody>
</table>

6.4.1.2 Seed spacing

<table>
<thead>
<tr>
<th>Nominal Corn spacing (cm)</th>
<th>Corn population per acre</th>
<th>CP3 percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>15.24</td>
<td>86000</td>
<td>56</td>
</tr>
<tr>
<td>25.40</td>
<td>52000</td>
<td>61</td>
</tr>
</tbody>
</table>
The CP3 percentages of the corn seed for the theoretical spacing of 15.24 cm and 25.40 cm were 56% and 61%, respectively. The estimated CP3 percentages were relatively low compared to the acceptable and recommended a CP3 percentage of 70% (ISO, 1984) for a precision planter. The CP3 percentage indicates the efficacy of a planter to place the seed at the correct theoretical spacing. Even (Figure 6.9a & 6.9b) and uneven (Figure 6.9c) spacing were observed. It was observed along the rows that they were misses, doubles and where larger gaps were observed could have been a possibility of seedling emergence failure (Figure 6.9). Figure 6.10 shows the spread of data points according to the 15.24 cm (high population) and 25.40 cm (low population) theoretical corn seed spacing. The downforce was determined to be independent of the seed spacing. The downforce had no significant difference in the population or field-corn spacing (p-value = 0.999 and the confidence levels from Tukey HSD had no zero value).

Figure 6.9  Corn plants in-row spacing. (a & b) represent good uniform spacing and (c) represent uneven or nonuniform seed spacing.
6.4.2 GPR measurements

The scanning process was as described in the methodology section. In the parallel scanning of furrows there were a lot of random hyperbolic responses which were mostly inconsistent with the seed depths (see example Figure 6.11), and in some cases, no random hyperbolic responses were recorded (see Figure 6.12). In Figure 6.11 & 6.12 no band-pass or finite impulse response filtering was performed because the faint hyperbolic responses were effectively discarded. Though some of the hyperbolic features may have been the resultant of the target or seeds at this point, it is incredibly complicated to differentiate the actual seed response from the noisy responses. The lack of quality response features also compounds to the difficulty to identify features from seeds. However, a common response feature across the parallel radargram was observed. The observed horizontal band features could be crucial towards identifying the furrow path (Figure 6.13).
When applying the smart time-dependent gains, horizontal band features across the radargrams were intensified, as shown in Figure 6.14, with some of the bands being consistent across replicated radargrams. Therefore, these horizontal bands at a prescribed travel time in the image could represent furrow features, although robust identification of the correct feature representing the furrow path could be a challenge. An approach to identify the furrow path based on the horizontal features was proposed.
The furrows were identified on the radargram collected perpendicular to the rows. All the 72 furrows were visible, as shown in Figure 6.15. Also, within the radargram, there were horizontal features with similar two-way travel times to the bands observed in parallel and perpendicular radargrams. If the two-way travel times are the same, then it is highly likely that the bands in the parallel and perpendicular radargrams are from the same feature. The perpendicular radargram was used as corresponding data to discriminate and identify features that could most likely result from the furrow path. Note that at planting, the pressure from the pressing wheels creates slight
compaction around the seeds to improve soil-seed contact. The compaction could be detected by the GPR of which at least one feature could probably be observed in parallel and perpendicular scans.

For clarity and interpretation of the perpendicular radargram, only twelve furrows are presented in the figure. The furrows are represented by the dips marked one to twelve. The dips occurred at the point the antenna crossed the two embankments or sidewall compaction indicated in Figure 6.6b. It was observed that they were contrasting features (white) towards the end of each dip or vee-like shape. That could suggest the detectability of the bottom of the furrow path or slight compaction from the pressing wheels. A compacted soil structure is denser and may have higher conductivity relative to surrounding soil matrix which then gives a white contrast in the radargram. Since the depth differences were infinitesimal, the vee-like shape feature profile appeared to be at the same position in the radargram. The phenomenon was observed across all the 72 furrows with a downforce of 354 N (36 furrows) in plot A and 451 N (36 furrows) in plot B. From the parallel and perpendicular radargrams; A-scans were extracted and plotted against each other, such as that in Figure 14. Using the A-scans infinitesimal time differences can effectively be calculated.

![B-scan of a 12-row precision planter collected perpendicular to the furrows with a downforce of 354 N.](image)

Figure 6.15  B-scan of a 12-row precision planter collected perpendicular to the furrows with a downforce of 354 N.
6.4.2.1 Extraction of the A-scans

A FORTRAN program was used to extract A-scans with respect to the baseline for visualization, interpretation, and analysis, as shown in Figure 6.16. The direct wave in Figure 6.16 to 6.22 are inconsequential in our analysis. Region (a) holds features that could be used for target identification. Region (b) represents a chaotic phenomenon which may be from multiple intermittent scattering due to the disturbed and unconsolidated or loose soil structure. Tillage disturbance loosens up the soils, which inherently creates a structure with varying physical properties, i.e., porosity, field capacity moisture, bulk density, friable clods, etc. The phenomenon was common across all B-scans collected. Region (c) are the features deep in the soil clearly pronounced as uniform ripples or horizontal bands within the radargram (see Figure 6.13 & 6.14). The horizontal bands could have been the results of consolidated soil layers that may have been caused by years of heavy machinery compaction, and or soil horizon with varying soil properties.

![Figure 6.16 A-scan showing features that may have resulted from the compaction zone of the pressing wheels or furrow path](image)

A background subtraction (BKG) was performed on the parallel and perpendicular raw A-scans. Figure 6.17 to 6.22 show the averaged non-target, parallel, and perpendicular A-scans corresponding to the 1.27 cm, 3.81 cm, and 6.35 cm planting depths at low and high downforce, respectively. At shallow depths, the effect of near-field zones (explained later) could have played a role in the
detectability of the furrow or compaction features. The response features indicating the presence of anomalies within the radargram were positioned at a deeper depth than the 1.5 ns time index. These response features could be caused by clutter and were randomly spread across the deeper end of the image. Nonetheless, these were features of no interest to our analysis, as shown in Figure 6.16 (region c). Also, these response features were present in the averaged non-target A-scan. Therefore clutter or unknown reflectors other than a furrow were detected buried deep in the soil matrix. Still, in Figure 6.17, there was no response feature that could be associated with the 1.27 cm depth. However, they were response features in Figure 6.18 & 6.19 identified between 0.575 ns to 1.5 ns. The response features could merely be a furrow path or the compaction zone from the pressing wheels. The green circle in Figure 6.18 & 6.19, and Figure 6.20 to 6.22 shows the features that could potentially be used to identify the furrow path or the compaction zone. The depths associated with the identified features could be calculated. The data demonstrated a suitable identification of features. To state that the features are from the two stated targets could be risky without further testing in multiple conditions.

Figure 6.17 A-scans represent features from 1.27 cm depth collected using a 354 N downforce in plot A.
Figure 6.18  A-scans represent features from 3.81 cm depth collected using a 354 N downforce in plot A.

Figure 6.19  A-scans represent features from 6.35 cm depth collected using a 354 N downforce in plot A.
Figure 6.20  A-scans represent features from 1.27 cm depth collected using a 451 N downforce in plot B.

Figure 6.21  A-scans represent features from 3.81 cm depth collected using a 451 N downforce in plot B.
Figure 6.22 A-scans represent features from 6.35 cm depth collected using a 451 N downforce in plot B.

6.4.2.2 Feature amplitudes

The more compact the sidewalls of the furrow a higher negative amplitude would be recorded and conversely true for less compacted sidewalls. Comparing the depths features from low and high downforces, respectively, it was observed that A-scans from high downforce were more pronounced. The A-scans are stable along the zero line with features readily identifiable after BKG, i.e., Figure 6.20 to 6.22. The feature amplitudes from high downforce were observed to be higher than those at low downforce. The phenomenon described above suggests that at a higher downforce soil uniformity was achieved while at low downforce it was unlikely to accomplish the latter. There are some feature amplitudes identified within the A-scan, however, their target origin was unknown.

6.4.2.3 Near-Field, Far-Field, and compaction zones

The depth difference was infinitesimal which could be a problem in the Near-Field Zone (NFZ). Too close or within the NFZ a target can be missed, and too far away, i.e., Far-Field Zone (FFZ) we lose clarity or resolution of the target. The area between the NFZ and FFZ referred to as the Fresnel zone (Jol, 2009) is an ideal place to detect a target without the obscurity of the NFZ effect and reduced resolution from the FFZ effect. The GPR strong electromagnetic pulse covers the radius within 1.5 wavelengths of the nominal antenna center frequency (Conyers, 2013). That is the dead zone area (state of no wave propagation), antenna ground coupling, followed by advancing divergent
beam such as that in Figure 6.23. The divergent beam is conical and traverses the material to some depth. In GPR scans the NFZ is characterized by little or few reflections with weak amplitudes. The reflections are usually at the surface to a certain depth. The NFZ varies with nominal center frequencies - at higher center frequencies the NFZ would be at shallow depths. The wavelength for a 2.6 GHz antenna is 11.5 cm. according to Jol (2009) the reactive NFZ would be approximately 2 cm.

![Figure 6.23 Near field, far field, and compaction zones.](image)

Ideally, at a higher frequency, i.e., 2.6 GHz, a depth equivalent to 2.54 cm (1 in) can be detected in the NFZ. Because of the distances being small, the antenna could possibly miss the shift because the difference is insignificant. The dead zone in Figure 6.23, represents an area where no target can be detected. The applied pressure from the press wheel creates a firm area on either side of the trench leaving the top-center of the closed furrow with seeds less compacted to enable seedling emergence. In that case, could the compaction zone affect the detectability of either the corn seeds or the furrow bottom? Deducing from the A-scan in Figure 6.14, the secondary response feature most likely represents the resultant of the compaction zone when the scan was collected parallel or along
the furrow. An argument can be made that the response feature was from the path of the furrow due to the planter opening the ground creating a pronounced furrow. By performing the BKG response features are more pronounced. The target A-scan (Figure 6.14) shows a response feature that is not present on the average no-target A-scan, which indicates the likelihood of the two possibilities stated above happening. Therefore, both cases are valid of which further experimentations can validate the ideas. Whether we can conclusively state that the furrow bottom is at the 1.27 cm, 3.81 cm, and 6.35 cm based on the field GPR data is too early to make the judgment.

### 6.4.2.4 GPR field data implications

The NFZ was profoundly interfering with GPR measurements. The interference was high which made it difficult to map corn or furrow depth, particularly at shallow depths, i.e., 1.27 cm. They could be a possibility that we were not finding any depth at all on the NFZ. The Fresnel zone could have been masked as well. The Fresnel zone is between the NFZ and FFZ where the scattering is calculated using the angular relationship of the waves. The surface furrow was the hardest to identify features. However, amidst the NFZ there were features outside the NFZ that were identified after BKG. The identified features, which could possibly be the furrow path or press wheel compaction zone, were between the 0.5 ns to 1.5 ns depths such as that in Figure 6.18 & 6.19, and Figure 6.20 to 6.22. By adjusting the zero-times, these times can be converted to depth using the depth law as shown in Equation 5.4.

### 6.5 Conclusion

The condition of the soils in the two plots were not ideal for sensing due to several unconsolidated variables that included soil clods, moist soils or field capacity moisture underneath the dry topsoil, rocks, hardened and friable clods, bone fragments, and other sedimental residuals. The planting depths were set to 3.81 cm, 6.35 cm, and 8.89 cm; however, due to conditions, the set planting depths translated to 1.27 cm, 3.81 cm, and 6.35 cm. In this study we present the following findings:

- The corn seed spacing and planting depths were manually measured after seedling emergence. The planter was determined to be inconsistent in the seed delivery to satisfy the objective. Substantial seed spacing and depth variations (standard deviation) were recorded. The planter failed to satisfy the CP3 and CPDA parameters.
• The two downforces were independent of the seed spacing. However, the downforces significantly affected the planting depths and variability (standard deviation).

• The effect of the two downforce pressure variances were detected with a 2.6 GHz GPR.

• The GPR data showed random hyperbolic response features which were inconsistent with corn seed depths.

• However, in the parallel and perpendicular radargrams, there were potential furrow path features which were effectively identified after background subtraction.

• The identified features were not converted to depths as more experimentations are needed to validate that the features represent the furrow path. The data presented limited scope to conclusively state that the identified features were from the furrow. Proof of concept has been successful, in that, response features from targets have been shown to exist in their nominal time frame.

6.5.1 Future work

For a future study, the plots need to be prepared in such a way that variables such as the hardened and friable clods, sedimental rocks, shrubs, and bones are minimized to maximize detectability. The planter depth setting needs to be set, and test runs conducted to assure nominal depths are correct. Further calibration investigation of the furrow features would be recommended as a goal to reduce false-positives of the furrow path. Further research is needed to corroborate the furrow feature findings in multiple conditions because from the data collected, we have a limited objective to define the features that can potentially be the furrow bottom and can be construed with the pressing wheel compaction. Moreover, place the antenna further from the soil surface to shift the near-field zone slightly outside the soil surface to avoid obscurity of the intended target. The antenna could be placed 2.54 cm to 7.62 cm (1 in. to 2 in.) away from the soil surface according to Jol (2009); Conyers (2013) reactive NFZ. A horn could be attached to set the antenna to a prescribed distance above the ground.
References


CHAPTER 7. GENERAL CONCLUSION

7.1 Conclusion

Literature has succinctly proven that corn planting depth has a recognizable impact in germination and seedling emergence uniformity or non-uniformity which definitely affects corn yield. The problem, however, is that corn depth is never known, and when measured is acquired conventionally or after seedling emergence. The purpose of this thesis was to bridge a gap in precision seeding. Measuring corn seeds planting depth using the conventional method requires time, energy, and the conventional technique is destructive to the seedbed. Additionally, corn seeds could be displaced from their initial suitable, and conducive place for germination and seedling emergence. Thus, a need to test and demonstrate a technological tool to assist farmers to measure planting depth and perhaps forecast their expected yield and assess precision planter performance is imperative. In the study, we investigated the use of Ground Penetrating Radar (GPR) for corn seed detection and estimation of planting depth in a closed trench. The utility of GPR to detect and quantify corn seed planting depth could be helpful in assessing the performance of a precision planter when seeding and knowledge of sown corn seeds depth may assist farmers.

Moreover, the implementation of closed-loop controllers for corn seeds depth could be possible, and prescription seeding maps could be developed for decision executions and management support. Henceforth, a five-part research study was carried out from 2016 to 2018 to identify a technological tool and measure corn seed planting depth on a closed furrow in different soils with varying conditions. Quantifying the planting depth was based on two-way travel time extracted from GPR data and the soil dielectric permittivity calculated from three models: (1) Topp’s dielectric, (2) soil mixing model, and (3) Topp-Mixing models. These three models used soil physical properties (soil volumetric moisture, free space parameter, composition, bulk density, and particle density) to estimate the permittivity which was essential to correct for the GPR wave velocity before computing depth. This chapter reports the final remarks of the five-part research carried out from 2016 to 2018;
1. Different nondestructive technologies that could be used to detect corn seeds in a closed trench were discussed. Though there was no single method identified to provide the solution to the problem comprehensively, the GPR was recommended as a viable technique to detect corn seed depth in a closed trench.

2. Numerical simulations indicated that corn seed models could be detected using a 1.6 and 2.6 GHz GPR in soils that have volumetric moisture content at field capacity. While in dry soils the simulation results indicate that real corn seeds may not be detected. It was observed that dielectric targets were difficult to detect. The dielectric target size and properties profoundly influenced the detectability.

3. Two GPR antenna nominal frequencies (1.6 and 2.6 GHz) were tested in sandy-loam and loam soils. In saline and high soil moisture soils, the two-system failed to detect the synthetic and natural field-corn seeds, respectively.

4. However, the 2.6 GHz antenna can detect the Pioneer P0339AMXT PDR field-corn variety with an average moisture content of 10.1% buried in dry soils (less than 5% soil moisture content) at three different depths and two population spacing. At intermediate moisture group (within 5% and 13%) the dielectric contrast could have been unsubstantial and moist (greater than 13%) the attenuation was higher which ultimately affected the detection of field-corn. Shallow planted field corn seeds were mapped while deep planted field-corn seeds were not mapped.

5. The simulation and experimental results provided contradicting information, particularly at low soil volumetric moisture content. In the numerical analysis the dielectric contrast played a vital role between the soil and seed model; hence a low moisture of 2.5% and 5%, the dielectric contrast was insignificant which led to weak response amplitude. During experimentation, the disparity between the dry soil physical properties, i.e., soil moisture and field-corn moisture led to detection. Also, experimental work shows that wetter soils were severely problematic to the GPR effectiveness to map the field-corn seeds which negated the simulation results.

6. The relationship between the corn seeds and soil physical properties were established using statistical analysis. Statistical methods were developed to identify the best soil conditions to detect field corn seeds and estimate planting depth with minimal error. The results were met with mixed success and challenging to interpret due to the nature of the problem (detecting a
dielectric target inside a dielectric host). The results showed that it was practically challenging to detect corn seeds in soil water contents that were at field capacity.

7. The Topp-Mixing model corrected effectively for the wave velocity which led to an improved CPDA of 8.37% compared to the Topp's dielectric and soil mixing model respectively.

8. Field experiments were conducted. The corn seed spacing and planting depths were manually measured after seedling emergence. The planter was determined to be inconsistent in the seed delivery to satisfy the objective. Substantial seed spacing and depth variations (standard deviation) were recorded. The planter failed to satisfy the CP3 and CPDA parameters.

9. The two downforces were independent of the seed spacing. However, the downforces significantly affected the planting depths and variability (standard deviation).

10. The effect of the two downforce pressure variances were detected with a 2.6 GHz GPR.

11. The GPR data showed random hyperbolic response features which were inconsistent with corn seed depths.

12. In the parallel and perpendicular radargrams, there were potential furrow path features which were effectively identified after background subtraction.

13. The identified features were not converted to depths as more experimentations are needed to validate that the features represent the furrow path. The data presented limited scope to conclusively state that the identified features were from the furrow.

14. The results are promising. However, more research is needed to enable detection and depth measurements of corn seeds in soil conditions that are typical of a plowed field. The overall implication of this work demonstrates that the GPR can provide an alternative to quantifying planting depth nondestructively.

7.2 Recommendations for Future work

Field-corn seeds have varying moisture contents at planting, and these moistures are not enough for detection when buried at field capacity moisture. As can be seen from the results the detection of buried corn seeds is a complicated task. Not all field-corn seeds can be detected should there be at the same depth, they will be those with slightly higher moisture contents and some will not which
present a challenge. However, the idea was not to detect all buried field corn in the laboratory if a pattern of detected corn seeds exists then by inter/extrapolation the depth can be determined.

1. One technological improvement that could make buried corn seeds detectable in soils could be to engineer a conductive substrate that can be used to coat seeds. The substrate should never interfere with the seed vigor, famine resistance, and genealogy et al. of the field-corn.

2. Though corn seeds were detected in dry soils, not all targets were detected in some replicates at deeper depths and high soil moisture. Further research perhaps with a slightly higher antenna frequency would be advisable to determine whether moving forward to more confounding factors such as soil moisture is necessary or perhaps combine the utility of GPR services with other nondestructive techniques to improve detection.

3. Though the GPR was recommended as the viable technique, in the review we also determined that no single technique was conclusively declared to be the best. Several of those techniques may be tested to determine an appropriate technique(s) to detect and measure planting depth nondestructively.

4. For a future study, the plots need to be prepared in such a way that variables such as the hardened and friable clods, sedimental rocks, shrubs, and bones are minimized to maximize detectability. The planter depth setting needs to be set, and test runs conducted to assure nominal depths are correct.

5. Further calibration investigation of the furrow features would be recommended as a goal to reduce false-positives of the furrow path. Further research is needed to corroborate the furrow feature findings in multiple conditions. From the data collected, we have a limited objective to define the features that can potentially be the furrow bottom and can be construed with the pressing wheel compaction.

6. Moreover, the antenna has to be placed further from the soil surface to shift the near-field zone slightly outside the soil surface to avoid obscurity of the intended target. The antenna could be placed 2.54 cm to 7.62 cm (1 in. to 3 in.) away from the soil surface according to Jol (2009); Conyers (2013) reactive NFZ. A horn could be attached to set the antenna to a prescribed distance above the ground.
APPENDIX A. DIELECTRIC PERMITTIVITY MODELS

Dielectric permittivity models used in estimating planting depths

Table A.1 Dielectric permittivity models

<table>
<thead>
<tr>
<th>Source</th>
<th>Dielectric permittivity model</th>
<th>Model name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Topp et al. (1980)</td>
<td>$\epsilon = 3.03 + 9.30\theta + 146\theta^2 - 76.7\theta^3$</td>
<td>Topps Dielectric</td>
</tr>
<tr>
<td>Peplinski et al. (1995)</td>
<td>$\epsilon = [1 + \left( \frac{\rho_b}{\rho_s} \right) \epsilon_s^\alpha + \frac{\rho_s^\beta}{\rho_v^\beta} - m_v] \left( \frac{1}{\alpha} \right)$</td>
<td>Soil Mixing</td>
</tr>
<tr>
<td></td>
<td>$\epsilon_s = (1.01 + 0.44\rho_s)^2 - 0.062$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\beta = 11.2748 - 0.519S - 0.152$</td>
<td></td>
</tr>
<tr>
<td></td>
<td>$\sigma_{eff} = -1.645 + 1.939\rho_b - 2.25622S + 1.594C$</td>
<td></td>
</tr>
<tr>
<td>Chapter 5 Equation 5.9</td>
<td>$\epsilon_{TM} = 4.90 + 0.64 M_i - 0.48 T_i$</td>
<td>Topp-Mixing</td>
</tr>
</tbody>
</table>

$\rho_b$ - soil bulk density, $\rho_s$ - particle density, $S$ - % sand, $C$ - % clay, $m_v$ and $\theta$ - soil volumetric moisture content, $\epsilon_{fw}^2$ - water dielectric permittivity. $\alpha = 0.65$
APPENDIX B. FEW ADDITIONAL PLANTING DEPTH DATA POINTS DETERMINED USING THE MATCH-UP AND SELECTION ALGORITHM

Esitmated dielectric permittivity and planting depths

Table B.1  Two-way travel time (TWTT) and dielectric permittivity sample data used to estimate corn seed planting depths in sandy-loam and loam soils at different moisture contents.

<table>
<thead>
<tr>
<th>Soil type</th>
<th>VMC (%)</th>
<th>TWTT (ns)</th>
<th>TM</th>
<th>SM</th>
<th>TD</th>
<th>DTM</th>
<th>DSM</th>
<th>DTD</th>
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<tr>
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<td>0.99</td>
<td>5.61</td>
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<td>6.27</td>
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<td>2.33</td>
<td>0.54</td>
<td>5.52</td>
<td>3.43</td>
<td>3.32</td>
<td>3.46</td>
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<tr>
<td>SL</td>
<td>2.95</td>
<td>0.90</td>
<td>5.61</td>
<td>3.65</td>
<td>3.43</td>
<td>5.71</td>
<td>7.10</td>
<td>7.30</td>
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<tr>
<td>LO</td>
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<td>0.58</td>
<td>5.46</td>
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<td>3.41</td>
<td>3.74</td>
<td>4.70</td>
<td>4.70</td>
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<tr>
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<td>5.43</td>
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<td>7.43</td>
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<td>5.42</td>
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<td>6.74</td>
<td>5.66</td>
<td>6.4</td>
<td>6.30</td>
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</tr>
<tr>
<td>SL</td>
<td>10.58</td>
<td>1.04</td>
<td>6.51</td>
<td>6.62</td>
<td>5.56</td>
<td>6.10</td>
<td>6.00</td>
<td>6.60</td>
</tr>
<tr>
<td>LO</td>
<td>13.28</td>
<td>1.40</td>
<td>6.14</td>
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<td>6.66</td>
<td>8.50</td>
<td>8.00</td>
<td>8.10</td>
</tr>
<tr>
<td>SL</td>
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<td>6.99</td>
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<td>7.20</td>
<td>6.30</td>
<td>6.80</td>
</tr>
<tr>
<td>SL</td>
<td>15.03</td>
<td>1.44</td>
<td>6.92</td>
<td>8.67</td>
<td>7.47</td>
<td>8.20</td>
<td>7.30</td>
<td>7.90</td>
</tr>
<tr>
<td>SL</td>
<td>15.74</td>
<td>1.67</td>
<td>6.98</td>
<td>9.02</td>
<td>7.81</td>
<td>9.50</td>
<td>8.40</td>
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<td>LO</td>
<td>17.06</td>
<td>1.52</td>
<td>6.28</td>
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</tr>
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<td>8.84</td>
<td>5.90</td>
<td>5.00</td>
<td>5.00</td>
</tr>
</tbody>
</table>

SL - sandy loam and LO - loam soils. TM - Topp-Mixing, SM - Soil mixing and TD - Topp’s dielectric models. DTM, DSM, and DTD - Depth estimated as function of Topp-Mixing, Soil mixing and Topp’s dielectric model and TWTT. The three dielectric models are unitless while predicted depths are in cm.