LIST OF FIGURES

Figure 2. 1. Conceptual model of SFCW radar showing signal reflections from topsoil and subsoil layers with corresponding A-scan response
Figure 2. 2. Working principle of SFCW radar, which transmits single-frequency waves sequentially across a defined frequency range
Figure 2. 3. Electromagnetic wave propagation of SFCW radar through three media: air, topsoil, and subsoil. Reflections occur at each interface due to impedance differences
Figure 2. 4. Measurement setup for the S21 parameter using a transmitting and receiving antenna connected to VNA port 1 and port 2, respectively. The reflected signal is recorded as S21 for further analysis
Figure 2. 5. Schematic illustration of radar scanning modes: (a) A-scan measures signal amplitude at a fixed point, (b) B-scan forms a 2D cross-sectional image from multiple A-scans, and (c) C-scan builds a 3D view by combining spatial scans over time.
Figure 2. 6. Positioning of the proposed research relative to previous studies highlighting improvements in topsoil thickness estimation using the SFCW radar method
Figure 3. 1. Proposed SFCW radar system architecture for topsoil thickness estimation. The system illustrates signal transmission, reflection subsurface layers and processing stages for identifying topsoil boundaries
Figure 3. 2. Simulation model for topsoil thickness estimation using SFCW radar. The process includes signal modeling, wave propagation across media, estimation, and final thickness calculation
Figure 3. 3. Laboratory setup for testing Topsoil thickness estimation using SFCW radar. The configuration simulates real soil conditions, enabling signal acquisition from layered media for method validation
Figure 3. 4. Field-testing simulation setup for Topsoil thickness estimation. The configuration demonstrates signal transmission and reflection in a soil environment using SFCW radar instrumentation.
Figure 3. 5. Workflow of the experimental data collection process, from radar system setup to A-scan and B-scan signal acquisition for topsoil thickness estimation.
Figure 3. 6. Top view of the experimental data acquisition setup: (a) fixed measurement point for A-scan, and (b) linear movement of the radar system in 2 cm steps for B-scan signal acquisition

Figure 4. 1. Effect of soil conductivity on topsoil thickness estimation. Higher conductivity increases signal attenuation, causing an overestimation in the detected thickness due to reduced subsurface reflection clarity
Figure 4. 2. Impact of SNR on topsoil thickness estimation. Accuracy is high a SNR ≥13 dB, but decreases significantly at lower SNR levels
Figure 4. 3. Effect of topsoil permittivity variation on thickness estimation accuracy. As the standard deviation of εr increases, indicating higher non-uniformity, the estimation accuracy decreases consistently
Figure 4. 4. Accuracy curves of topsoil thickness estimation and the variation leve of topsoil ɛr for three SNR values (10 dB, 20 dB, and 30 dB)
Figure 4. 5. A-scan signals for various topsoil thicknesses. Greater thickness results in longer time delays, shown by the shift of reflection peaks to the right40
Figure 4. 6. B-scan image showing variations in topsoil thickness. The upper and lower reflection lines indicate the ground surface and the topsoil-subsoil boundary respectively.
Figure 4. 7. A-scan signal at different radar heights: (a) 0 cm, (b) 10 cm, (c) 20 cm (d) 30 cm, and (e) 40 cm. Surface reflection is absent at 0 cm and becomes more distinguishable as the height increases, with optimal separation observed at 30 cm
Figure 4. 8. Cumulative average change in estimated topsoil thickness based on the number of measurements from 1 to 100 times
Figure 4. 9. Standard deviation and accuracy at each measurement point for 25 cm and 30 cm radar heights: (a, b) standard deviation and (c, d) accuracy. Standard deviation remains good across all points, while accuracy significantly improves a 30 cm compared to 25 cm
Figure 4. 10. Underground aluminum placement setup in box
Figure 4. 11. Comparison of A-scan signals for different soil thicknesses using ar aluminium plate as subsurface reflector. The third peak shifts rightward as thickness increases, indicating longer signal travel time.
Figure 4. 12. A-scan comparison for different soil thicknesses without ar aluminium reflector. The third peak shifts rightward with increasing depth, but with lower amplitude due to weaker subsurface reflection

Figure 4. 13. A-scan signals under weed-free and weed-covered surface conditions at (a) Location 1 and (b) Location 2
Figure 4. 14. Topsoil thickness estimation accuracy at seven measurement locations under (a) weed-covered and (b) weed-free surface conditions
Figure 4. 15. Precision of topsoil thickness estimations at seven field locations under (a) with weed condition and (b) without weed conditions
Figure 4. 16. B-scan measurement setup: (a) surface with weed cover (b) surface after weed removal.
Figure 4. 17. B-scan validation and image comparison at Loc 1: (a) soil profile after excavation, (b) B-scan with weeds condition, (c) B-scan without weeds condition.
Figure 4. 18. B-scan validation and image comparison at Loc 2: (a) soil profile after excavation, (b) B-scan with weeds condition, (c) B-scan without weeds condition
Figure 4. 19. B-scan validation and image comparison at Loc 2: (a) soil profile after excavation, (b) B-scan with weeds condition, (c) B-scan without weeds condition
Figure 4. 20. Quantitative comparison under weed-free conditions: (a) line plot of actual and estimated values, (b) scatter plot with ideal line reference64
Figure 4. 21. Quantitative comparison under weed-covered condition: (a) line plot of actual and estimated values, (b) scatter plot with ideal line reference65
Appendix A. 1. Comparison of A-Scan at Loc 1 (with and without weeds)74
Appendix A. 2. Comparison of A-Scan at Loc 2 (with and without weeds)74
Appendix A. 3. Comparison of A-Scan at Loc 3 (with and without weeds)75
Appendix A. 4. Comparison of A-Scan at Loc 4 (with and without weeds)75
Appendix A. 5. Comparison of A-Scan at Loc 5 (with and without weeds)75
Appendix A. 6. Comparison of A-Scan at Loc 6 (with and without weeds)76
Appendix A. 7. Comparison of A-Scan at Loc 7 (with and without weeds)76
Appendix A. 8. Radar Reflection on Layers with Different Characteristics77

Appendix A. 9. Thickness Variation at Radar Height 40 cm
Appendix A. 10. Radar Height Variation
Appendix A. 11. Radar Height Variation with Aluminium on the Ground Surface
Appendix A. 12. Radar Height Variation without Aluminium on the Ground Surface
Appendix A. 13. Reflection Signal at Radar Height 9 cm
Appendix A. 14. Reflection Signal at Radar Height 21 cm
Appendix A. 15. Reflection Signal at Radar Height 30 cm with Thickness 30 cm.
Appendix A. 16. Reflection Signal at Radar Height 40 cm with Thickness 30 cm.
Appendix A. 17. Reflection Signal at Radar Height 30 cm with Thickness 40 cm.
Appendix A. 18. Reflection Signal at Radar Height 40 cm with Thickness 40 cm.
Appendix A. 19. Reflection Signal at Radar Height 30 cm with Thickness 50 cm
Appendix A. 20. Reflection Signal at Radar Height 40 cm with Thickness 50 cm.
Appendix A. 21. A-Scan Signal for Different Radar Height and Different Soil Thickness
Appendix C. 1. B-Scan Uneven Soil Surface (Soil in Box)
Appendix C. 2. B-Scan of Object Underground89
Appendix D. 1. Manual Measurement at Loc 190
Appendix D. 2. Manual Measurement at Loc 2
Appendix D. 3. Manual Measurement at Loc 390
Appendix D. 4. Manual Measurement at Loc 4

Appendix D. 5. Manual Measurement at Loc 5.	91
Appendix D. 6. Manual Measurement at Loc 6.	92
Appendix D. 7. Manual Measurement at Loc 7.	92
Appendix E. 1. Distance between A-Scan locations 1 and 2	93
Appendix E. 2. Distance between A-Scan locations 2 and 3	93
Appendix E. 3. A-Scan Data Collection under Existing Weed Conditions	94
Appendix E. 4. A-Scan Data Collection under Weed-Free Conditions	94
Appendix E. 5. A-Scan data collection using aluminum on the ground surfaction obtain maximum reflection.	
Appendix E. 6. B-Scan Data Collection with Weeds Condition.	95
Appendix E. 7. B-Scan Data Collection without Weeds Condition.	96
Appendix E. 8. Manual measurement at each B-Scan point	96
Appendix F. 1. Soil box for data collection in the laboratory	97
Appendix F. 3. Data collection in the laboratory.	97
Appendix F. 4. Maximum reflection data collection using aluminum on the groin the laboratory.	
Appendix F. 5. Underground reflection data collection using aluminum at bottom of a soil box in the laboratory	