Soil Moisture Estimation from GPR Hyperbola Fitting in the Agricultural Root Zone

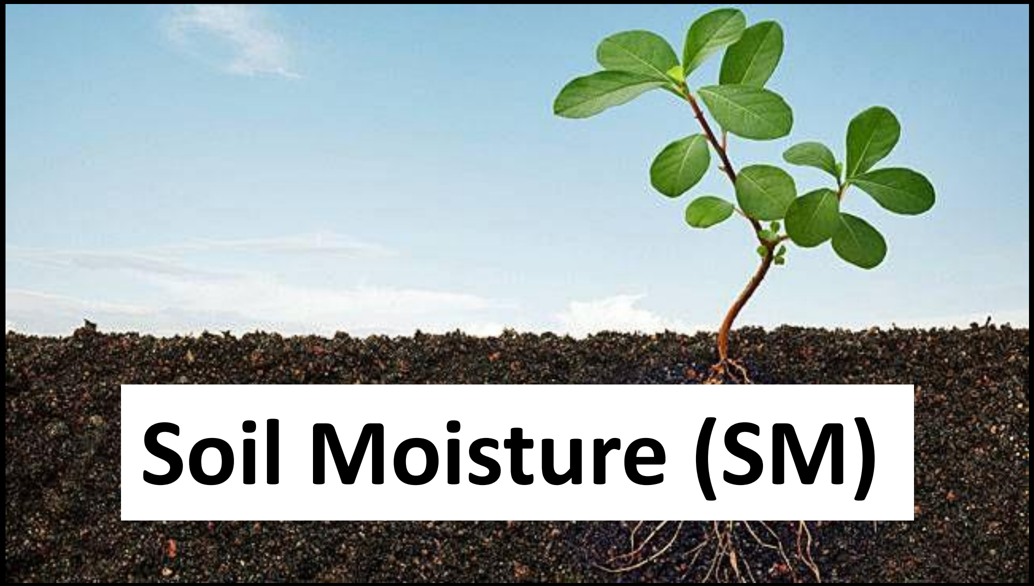
Chameera Illawathure[1], Gary Parkin[2], Sebastien Lambot[3], Lakshman Galagedara[1]

[1]School of Science and the Environment, Memorial University of Newfoundland, Corner Brook, NL, Canada

[2]School of Environmental Science, University of Guelph, Guelph, ON, Canada

[3]Earth and Life Institute, Environmental Sciences, Université catholique de Louvain, Louvain-la-Neuve, Belgium

Introduction



30 cm

>60% of the root biomass of most temperate crops → in upper 30 cm soil

Oat, Soybean, Canola, Wheat, Alfalfa
61–76% of roots → in 30 cm soil

Fan et al., 2016

Introduction

Gravimetric SM measurement

- Standard and direct method
- Destructive
- Time-consuming

Introduction

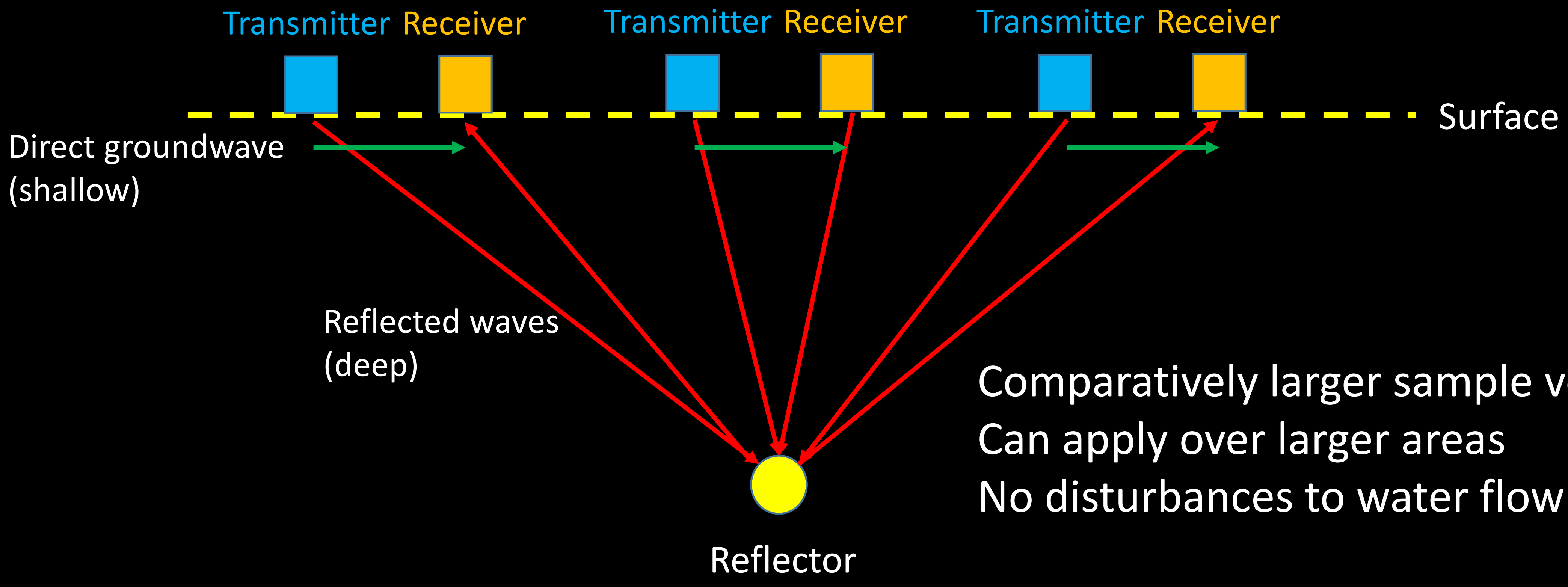
Time-Domain-Reflectometry (TDR) probes for SM estimation

Most commonly used indirect method
[researchers and practitioners]

Difficult in large-scales
[small sample volume, point measurement, disturb water flow paths etc.]

Introduction

Ground Penetrating Radar (GPR)

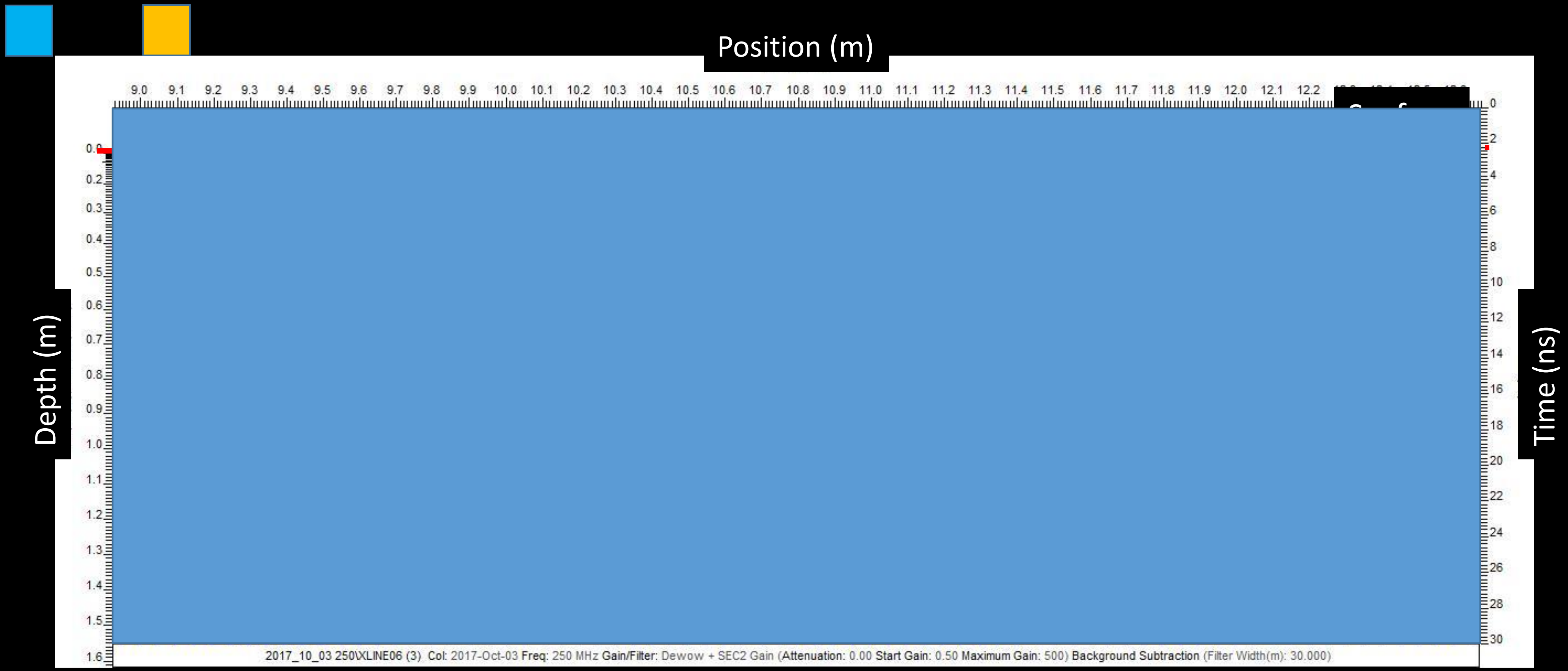


Comparatively larger sample volume
Can apply over larger areas
No disturbances to water flow paths

Davis and Annan, 1989

Introduction

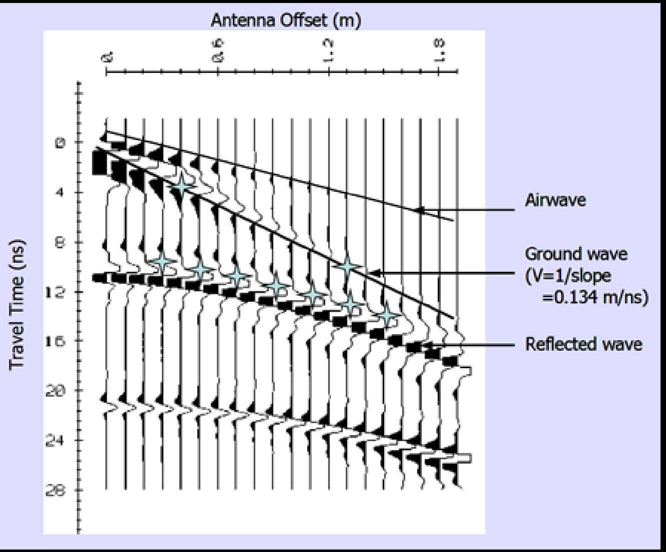
Transmitter Receiver

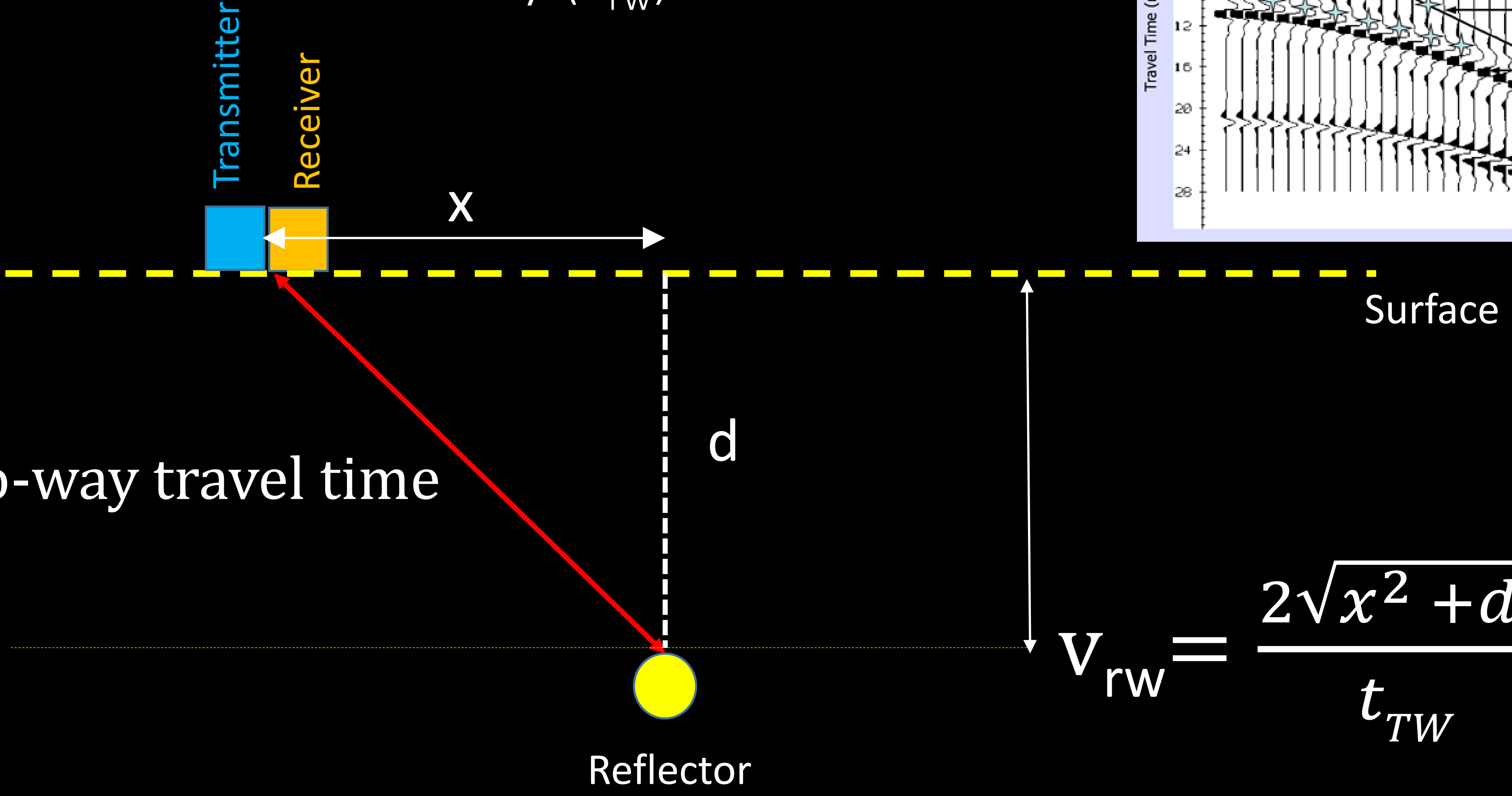


Annan, J.P. 2004 (Sensors and software Inc.); Maas and Schmalzl, 2013

Introduction

Average reflected wave velocity (v_{rw})





t_{TW} = two-way travel time

$$V_{rw} = \frac{2\sqrt{x^2 + d^2}}{t_{TW}}$$

Davis and Annan, 1989; Huisman et al., 2003

Introduction

$$V_{rw} \Rightarrow \varepsilon_r \Rightarrow \theta_v$$

V_{rw} –> Relative dielectric permittivity –> Volumetric water content

$$\theta_v = -5.3 \times 10^{-2} + 2.92 \times 10^{-2} \varepsilon - 5.5 \times 10^{-4} \varepsilon^2 + 4.3 \times 10^{-6} \varepsilon^3$$

Davis and Annan, 1989; Topp et al., 1980

Research Problems

- GPR estimates an average θ_v of a comparatively larger sampling volume
- TDR provides point measurements, relatively smaller sample volume

Evaluating GPR estimations using TDR is difficult

- Because, agricultural soils are mostly heterogeneous (high spatial variability)

Corresponding soil volume of estimated v_{rw} from hyperbola analysis is unclear

Hyperbolic reflections especially in the upper 30 cm of a GPR profile are not easy to identify (generally noisy data)

Objectives

Using hyperbola fitting method to,

(i) determine the soil volume of GPR when estimating V_{rw} using the hyperbola method and

(ii) evaluate a practical GPR-based reflection approach to estimate SM within the upper 30 cm of the soil profile.

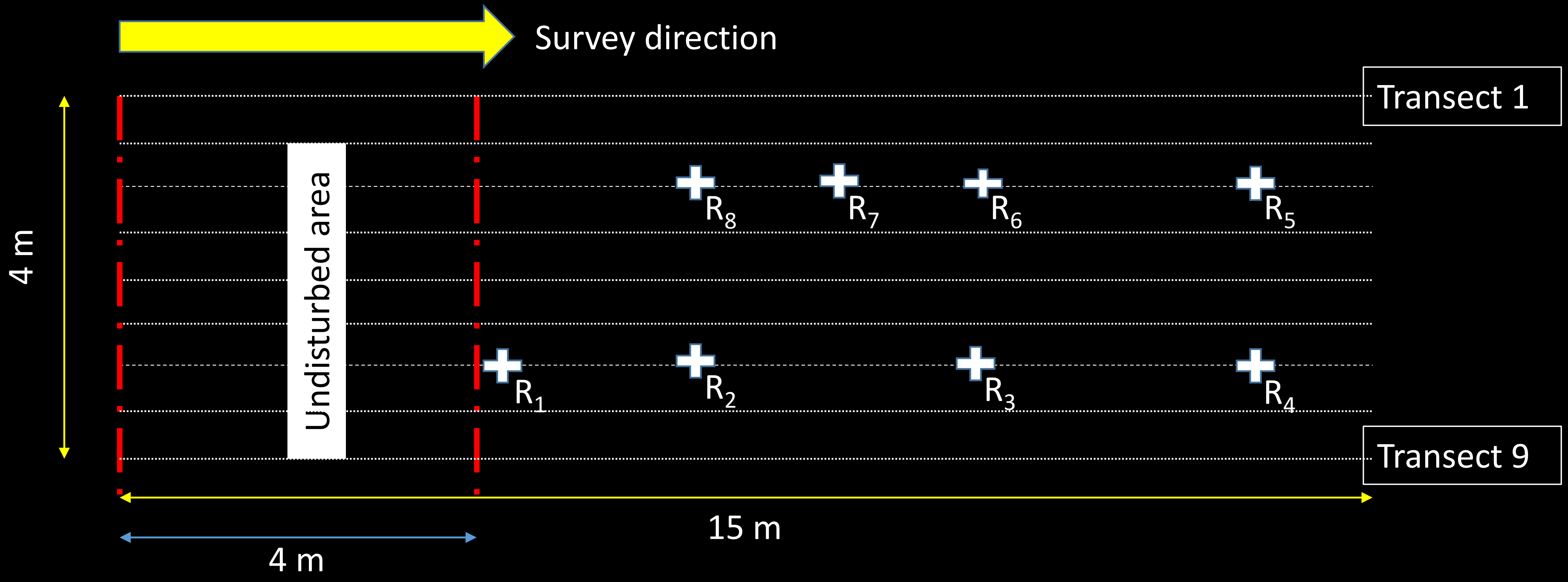
Study Area

- Western Newfoundland, Canada
- Flat land
- Shallow water table
- Unconfined loamy sand (fairly uniform) aquifer

www.googlemaps.com

Methods

Experimental setup



Not to scale

Methods

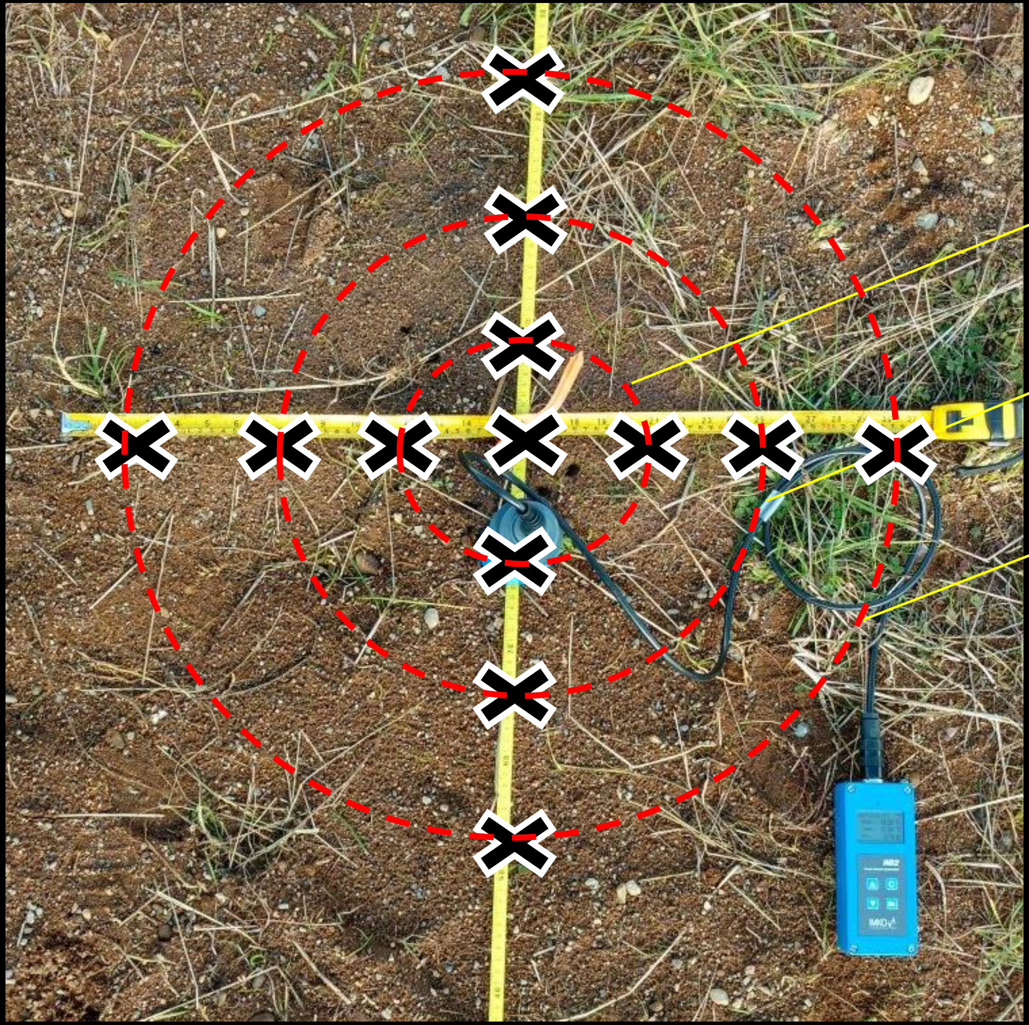
GPR survey methods

Common-Offset (CO)

Common-Mid-Point (CMP)

Methods

TDR data collection from a buried location (plan view)



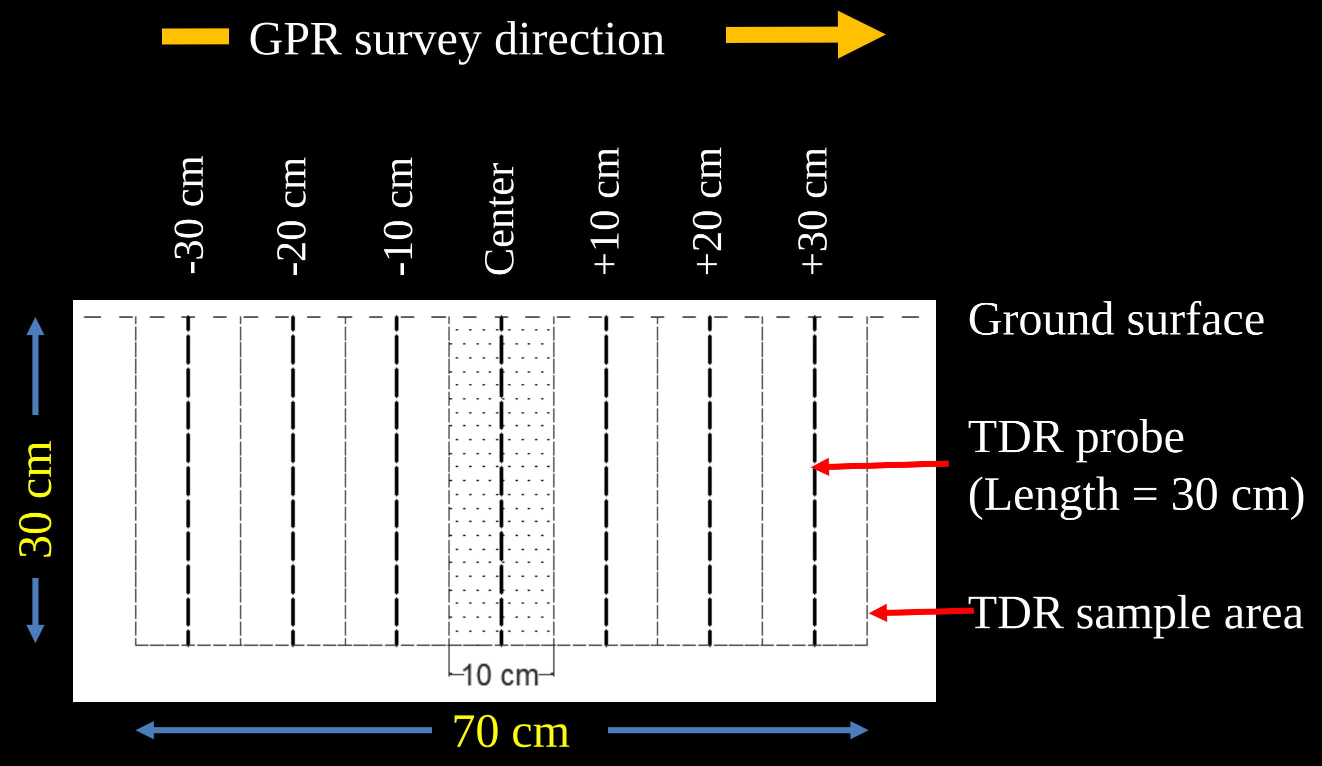
r = 10 cm

r = 20 cm

r = 30 cm

Methods

SM data collection using TDR from a buried location (vertical cross section along the GPR survey)



Methods

GPR & TDR Data Collection Schedule

Day	GPR			TDR
	250 MHz	500 MHz	1000 MHz	
1		CO grid		
2	CO grid	CO grid	CO grid	
3		CO + CMP		30 cm probe
4			CO + CMP	30 cm probe
5	CO grid	CO grid	CO grid	30 cm probe
6	CO grid	CO grid	CO grid	30 cm probe
Antenna separation for CO survey	**38 cm**	**22.5 cm**	**15 cm**	

500 MHz was selected for the detailed analysis

Results and Discussion

TDR probe calibration

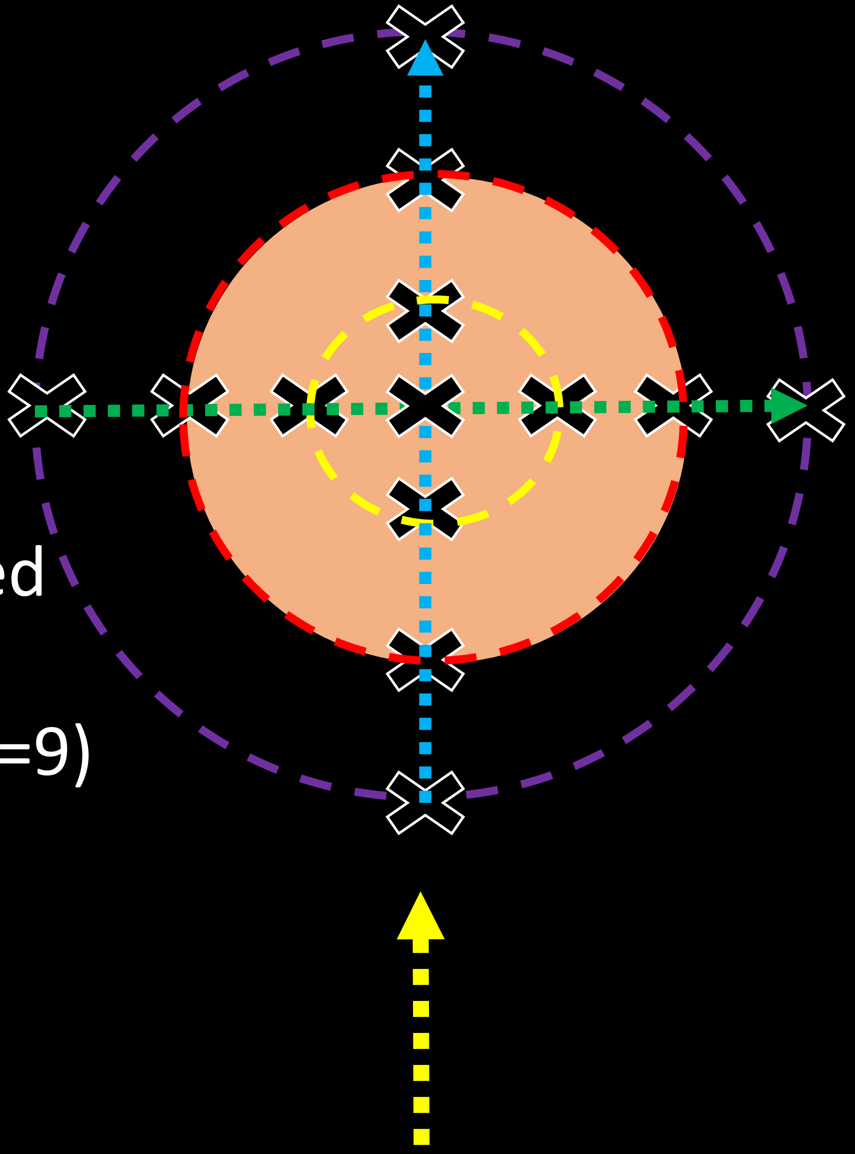
Θ_v (m^3/m^3)		*n*	RMSE (m^3/m^3)
Gravimetric	TDR		
0.09 - 0.16	0.10 - 0.18	21	0.016

Average bulk density = 1.39 ± 0.09 g cm^{-3} (n=6)

RMSE = Root Mean Squared Error

Results and Discussion

Determine GPR-hyperbola sampling volumes using TDR as the reference (Objective 1)



TDR1: all TDR measurements collected at a buried location (*n*=13)

TDR2: up to 20 cm radius including the center (*n*=9)

TDR3: only 10 cm radius (*n*=4)

TDR4: only at 20 cm (*n*=4)

TDR5: only at 30 cm (*n*=4)

TDR6: across the transect (*n*=7)

TDR7: along the transect (*n*=7)

GPR survey direction

Results and Discussion

Statistical comparison of 30 cm long TDR average θ_v and 500 MHz GPR-hyperbola estimated θ_v

[RMSE value, Mann-Whitney test, p-value]

Hyperbola depth (cm)	*n*	TDR average						
		TDR1	TDR2	TDR3	TDR4	TDR5	TDR6	TDR7
		13	9	4	4	4	7	7
27 - 34	9	0.023	0.024	0.026	0.022	0.023	0.023	0.024
		0.427	0.348	0.653	0.236	0.391	0.270	0.178
34 - 50	9	0.036	0.041	0.045	0.037	0.027	0.033	0.039
		0.185	0.057	0.185	0.133	0.426	0.157	0.157
27 - 50	18	0.030	0.033	0.037	0.031	0.025	0.029	0.032
		0.117	0.079	0.159	0.069	0.200	0.103	0.079

Results and Discussion

Evaluating a practical approach (Objective 2)

Analysis was done using 500 MHz GPR

Common-Offset (CO)

Common-Mid-Point (CMP)

Results and Discussion

For a 30 cm deep hyperbola

GPR-hyperbola sampling areas of CO and CMP methods with respect to TDR sampling area

CO

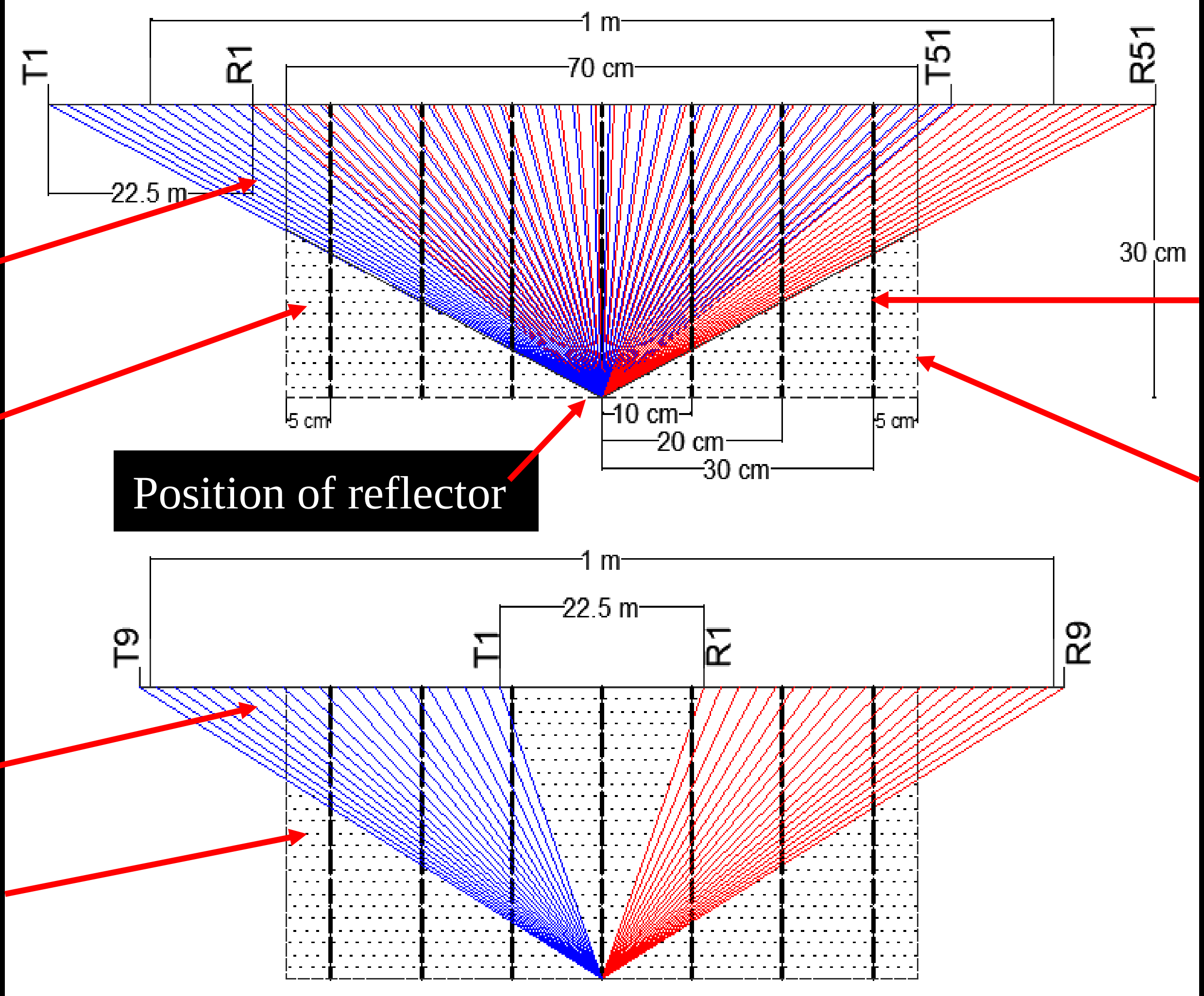
Unrelated area covered by CO

Area not covered by CO

CMP

Unrelated area covered by CMP

Area not covered by CMP



Ground surface

TDR probes

TDR sample area

Results and Discussion

For a 30 cm deep hyperbola

GPR-hyperbola sampling areas of CO and CMP methods with respect to TDR sampling area

	Total GPR sample area (cm^2)	TDR sample area covered by GPR	Unrelated area out of total GPR sample area
CMP	1200.0	49.8 %	12.9 %
CO	1837.5	**71.4 %**	18.4 %
Total TDR sample area (70 cm × 30 cm) = 2100 cm^2			

Results and Discussion

For a 30 cm deep hyperbola

RMSE ($m^3\ m^{-3}$) of 500 MHz GPR-estimated (CO and CMP methods) and 30 cm TDR-measured θ_v

GPR Method	Sample size*	Average TDR θ_v along the transect		
		10 cm (*n*=3)	20 cm (*n*=5)	30 cm (*n*=7)
CMP – hyperbola fitting	6	0.054	0.054	0.055
CO – hyperbola fitting	6	**0.018**	**0.021**	**0.020**

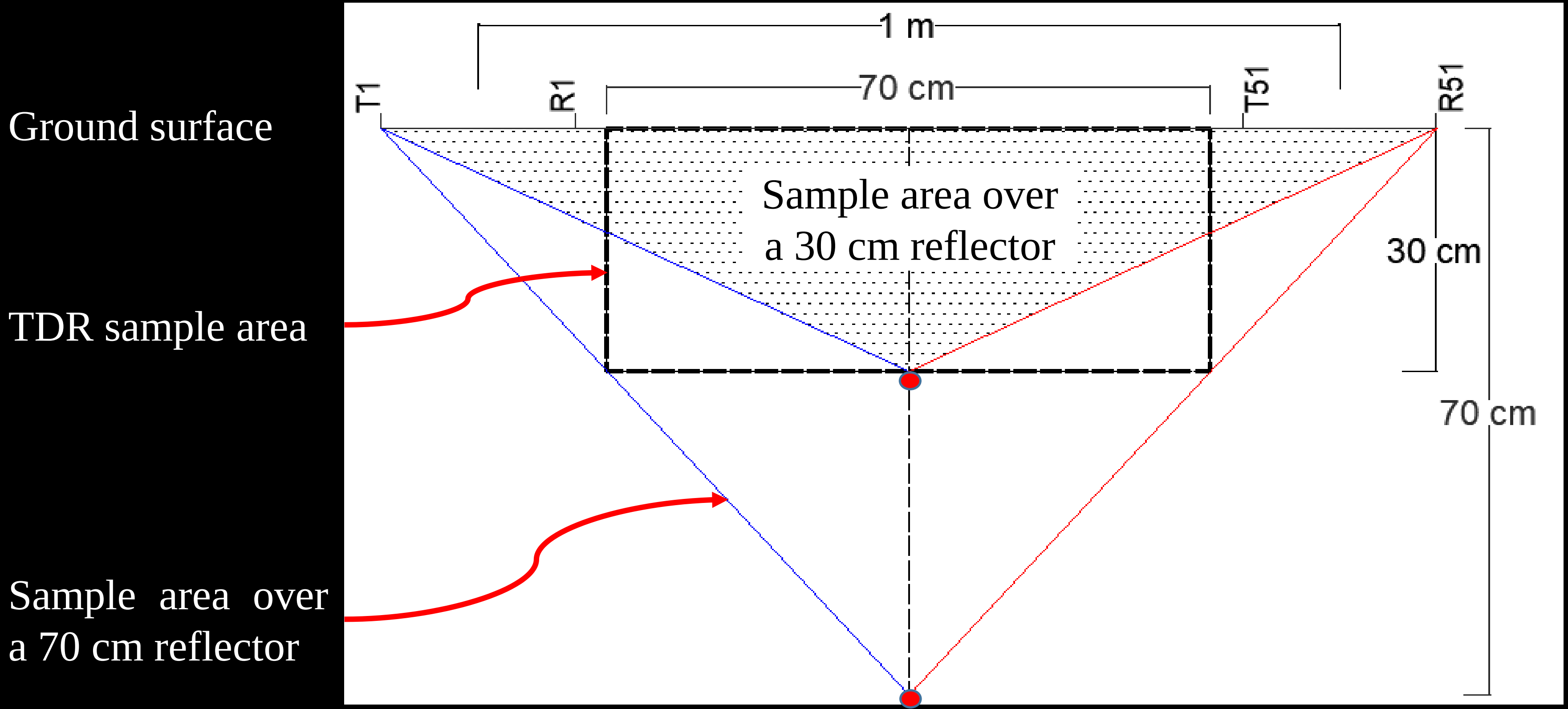
*Sample size = number of buried reflectors

n = number of TDR data

Results and Discussion

For 30 cm and 70 cm deep hyperbolas

GPR-hyperbola sampling areas of CO method for different reflector depths with respect to TDR sampling area



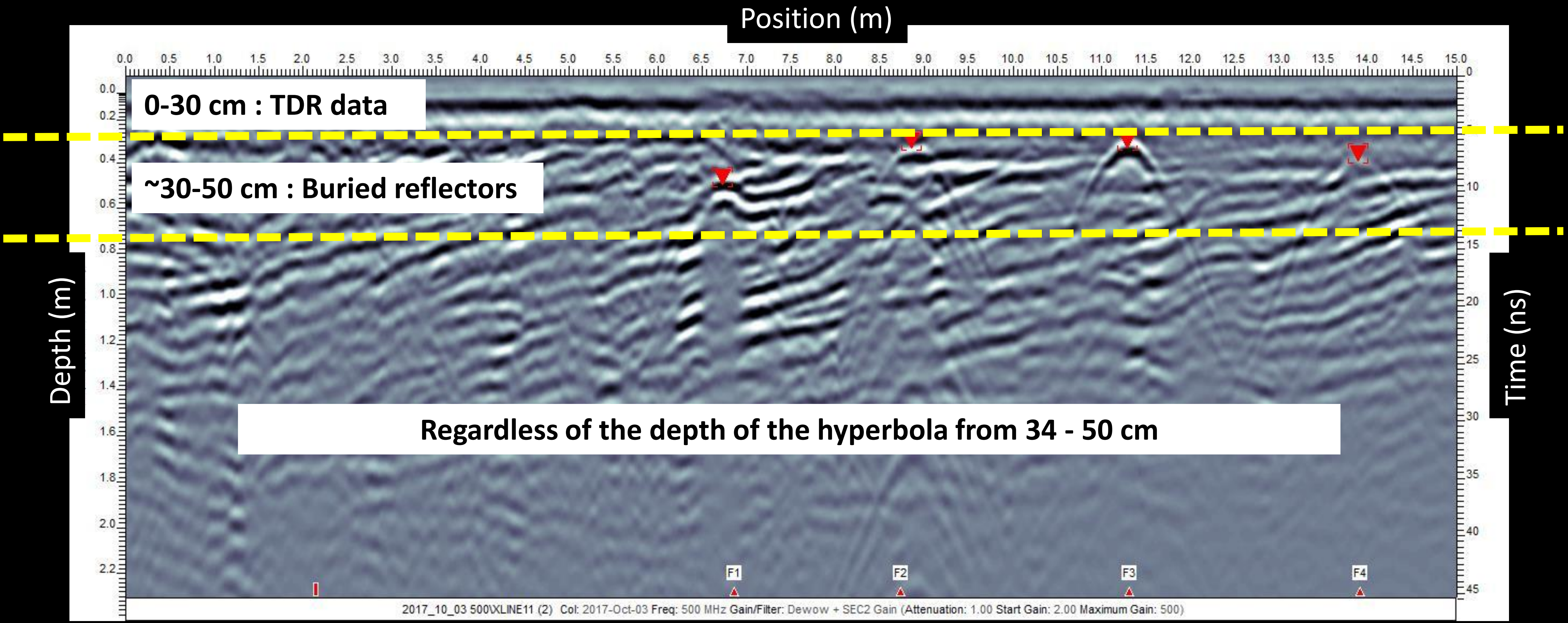
Results and Discussion

GPR-hyperbola sampling areas of CO method with respect to TDR sampling area at different hyperbola depths

Depth of hyperbola (cm)	TDR sample area covered by GPR	Unrelated area out of total GPR sample area	
		0 - 30 cm	30 - 70 cm
30	71.4 %	18.4 %	-
70	**100 %**	18.4 %	**32.6 %**

Results and Discussion

Evaluating a practical approach (Objective 2) cntd.



Results and Discussion

Statistical comparison of 30 cm long TDR average θ_v and 500 MHz GPR-hyperbola estimated θ_v

[RMSE value, Mann-Whitney test, p-value]

Hyperbola depth (cm)	*n*	TDR average						
		TDR1	**TDR2**	**TDR3**	**TDR4**	**TDR5**	**TDR6**	**TDR7**
		13	9	4	4	4	7	7
27 - 34	9	0.023	0.024	0.026	0.022	0.023	0.023	0.024
		0.427	0.348	0.653	0.236	0.391	0.270	0.178
34 - 50	9	0.036	0.041	0.045	0.037	0.027	0.033	0.039
		0.185	0.057	0.185	0.133	0.426	0.157	0.157
27 - 50	18	0.030	0.033	0.037	0.031	0.025	0.029	0.032
		0.117	0.079	0.159	0.069	0.200	0.103	0.079

Conclusion 1

Under the tested site conditions,

TDR-measured θ_v of a 30 cm deep soil volume with a 30 cm radius was not statistically different with GPR-measured θ_v by analyzing up to 50 cm deep hyperbola reflection

(RMSE = 0.03 $m^3\ m^{-3}$, p-value = 0.117).

When comparing reflections from a 30 cm deep point reflector along 1 m GPR survey length using CO and CMP methods,

The CO method covered 71.4 % of the TDR sample area (30 cm × 70 cm) compared to 49.8 % from the CMP method.

Conclusion 2

The proposed hyperbola fitting method agreed with 30 cm long TDR probe data with an RMSE of;

$0.02\ m^3\ m^{-3}$ for a shallow hyperbola (27 – 34 cm),

$0.04\ m^3\ m^{-3}$ for a deeper hyperbola (34 – 50 cm), and

$0.03\ m^3\ m^{-3}$ for hyperbola depths 27 – 50 cm.

This is a noninvasive practical approach to estimate SM rapidly with a relatively large sample volume in shallow agricultural root zones.

Future work

Evaluating the GPR estimated θ_v with a systematic TDR probes arrangement along the GPR transect is recommended.

Probe arrangement should be compatible with the GPR sample geometry (i.e., long TDR probes at the top of the reflector and shallow probes towards both sides of the transect).

Illawathure *et al.*, 2019. Hydrological Processes. Revision requested.

References

- Annan, J.P. 2004. Ground Penetrating Radar: Principles, Procedures and Applications. Sensors and Software Inc, Ontario.
- Canadian Society of Soil Sciences. 2007. 'Soil Sampling and Methods of Analysis', Second Edition. Boca Raton: CRC Press.
- Davis, J.L., Annan, A.P. 1989. 'Ground-penetrating radar for high-resolution mapping of soil and rock stratigraphy', Geophysical Pros. 37, 531-551.
- Fan, J., McConkey, B., Wang, H., Janzen, H. 2016. 'Root distribution by depth for temperate agricultural crops' Field Crops Research, 189, 68-74.
- Galagedara, L. W., Parkin, G. W., Redman, J. D. 2003. 'An analysis of the ground-penetrating radar direct ground wave method for soil water content measurement', Hydrol. Process. 17(18), 3615-3628.
- Greaves, R.J., Lesmes, D.P., Lee, J.M., Toksoz, M.N. 1996. 'Velocity variations and water content estimated from multi-offset, ground-penetrating radar', Geophysics 61, 683-695.
- Grote, K., Hubbard, S.S., and Rubin, Y. (2003). Field-scale estimation of volumetric water content using GPR ground wave techniques. Wat. Resour. Res., vol. 39, No.11, 1321.
- Huisman, J., Hubbard, S. S., Redman, J. D., Annan, A. P. 2003. 'Measuring soil water content with ground penetrating radar: A review', Vadose Zone Journal 2, 476-491.
- Lunt, I.A., Hubbard, S., Rubin, Y. 2005. 'Soil moisture content estimation using ground-penetrating radar reflection data', J. Hydrol. 307, 254-269.
- Maas, C., Schmalzl, J. 2013. 'Using pattern recognition to automatically localize reflection hyperbolas in data from ground penetrating radar', Computers & Geosciences 58, 116-125.
- Takeshita, Y., Kobayashi, H., Kazunori Tao, I., & Kaihotsu, I. 2004. 'Measurement of groundwater behavior in sandy soils using surface ground penetrating radar', Proceed. Tenth Int. Con. Ground Penetrating Radar, 517-520.
- Topp, G. C., Davis, J. L. & Annan A.P. 1980. 'Electromagnetic determination of soil water content: Measurements in coaxial transmission lines', Water Resour. Res. 16(3), 574–582.
- Tilman, D., Balzer, C., Hill, J., Befort, B. 2011. 'Global food demand and the sustainable intensification of agriculture', Proceed. of the Nat. Aca. of Sci. 108 (50) 20260-20264.

Acknowledgements

Ignite R&D Funding
Research and Development Cooperation (InnovateNL), Govt. of NL

Research Office
Grenfell Campus, Memorial University of Newfoundland

Collaborators & Research Site
Pynn's Brook Research Station – Dept. of Fisheries and Land Resources, Govt. of NL

Thank you!