Environmental Effects on Brightness Temperature Observation from an L-band Radiometer

Thi Mai Nguyen, *Graduate Student Member, IEEE*, Jeffrey P. Walker, *Fellow, IEEE*, Nan Ye, *Member, IEEE*, and Jayantha Kodikara.

***Abstract*—Measuring the microwave brightness temperature (TB) using a radiometer is important for estimating soil moisture (SM). However, no study has demonstrated the effect of environmental conditions on these measurements. With this technology being explored for use in precision agriculture, indoor application and/or utilization in environments close to buildings becomes a certain reality. Therefore, an experiment was conducted in a warehouse of concrete and steel construction to investigate this issue. An L-band microwave radiometer known as ELBARA III was used to measure the surface TB over a soil box at different incidence angles and moisture contents. An environmental correction equation was applied to offset the effect of the indoor environment on the TB observed by the sensor. Accordingly, the effect of the TB environment on the TB observations at different incidence angles and moisture contents were analyzed. The environment correction equation provided a substantial improvement in estimating the direct TB emitted from the soil relative to model estimates with a reduction in root-mean-squared error (RMSE) from 57 K to 4 K. Overall, the results demonstrated that the built environment had a substantial influence on the TB observed by the sensor, and that it was not possible to directly use indoor measurements for reliable SM retrieval. Use of the environment correction equation offers inspiration for SM retrieval from indoor measurements, but further studies are required. This result provides an early glimpse into the ability of microwave radiometers for SM monitoring in indoor environments.**

***Index Terms*— Passive microwave remote sensing, brightness temperature, indoor measurement, environment effect correction.**

I. Introduction

It has been known for more than four decades that SM can be retrieved from thermal radiance obtained with an L-band radiometer [1]. This understanding has led to the Soil Moisture and Ocean Salinity (SMOS) mission launched by the European Space Agency in 2009 [2] and the Soil Moisture Active Passive (SMAP) mission launched by the National Aeronautical and Space Administration in 2015 [3]. Moreover, L-band (1–2 GHz) microwave radiometry has been proven as the most accurate approach for remote SM retrieval when compared to other methods [4]. However, because of the nature of the technology and the satellite altitude, the current spatial resolution from space is approximately 40 km [5]. Nevertheless, it is possible to deploy this technology closer to the ground, such as from a fixed location, vehicle or drone, so that a spatial resolution of less than 10 m can be achieved. SM retrieval by ground-based or aircraft-mounted radiometers operating at L-band has been proven in several previous studies [6, 7]. It has even been done from a drone [8] and by mounting directly onto machinery [9].

The radiometer measures microwave radiation, also known as the brightness temperature (TB), that can be converted into SM using a radiative transfer model. Previous studies [10] have demonstrated the impact of radiation sources and environmental factors on TB observed from these sensors. The atmospheric contribution to TB measured from the ground in clear and cloudy conditions has also been analyzed [11, 12]. Moreover, the Earth's atmosphere is contaminated by man-made radio-frequency interference (RFI) sources that increase the observed TB [13]. Therefore, detecting and minimizing these factors is an important issue in microwave remote sensing measurement. However, previous studies have only taken into account the environmental effects from outdoor measurements, and no study has shown the effect of environmental conditions on indoor remote sensing measurements. Accordingly, this letter seeks to demonstrate the effects of the indoor environment on passive microwave remote sensing measurement. Consequently, an environmental correction equation was applied to calculate the radiation obtained by the L-band radiometer antenna directly from the observed surface under indoor environment conditions, and the ability to then use it for SM estimation assessed.

II. DATASETS

As part of the long-term validation program of SMOS, three identical L-band radiometer systems were commissioned by ESA called ELBARA (L-band radiometer), manufactured by Gamma Remote Sensing in Switzerland [14]. These are based on the Dicke radiometer concept with an internal two-point calibration system. ELBARA-III (Third-generation) is a portable ground-based passive microwave radiometer system based on this same technology and used in this analysis. It has a Pickett-type horn antenna that has evolved from ELBARA-II

Manuscript received …; revised …; accepted …. Date of publication…; date of current version …. This research work is a part of a research project (Project No IH18.03.2) sponsored by the Smart Pavements Australia Research Collaboration (SPARC) Hub (https://sparchub.org.au) at the Department of Civil Engineering, Monash University, funded by the Australian Research Council (ARC) Industrial Transformation Research Hub (ITRH) Scheme (Project ID: IH180100010) (*Corresponding author: Thi Mai Nguyen).*

Thi Mai Nguyen, J. P. Walker, Nan Ye, and Jayantha Kodikara are with the Department of Civil Engineering, Monash University, Melbourne, VIC 3800, Australia (e-mail: thi.nguyen9@monash.edu).

This article has been accepted for publication in IEEE Geoscience and Remote Sensing Letters. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/LGRS.2022.3215937

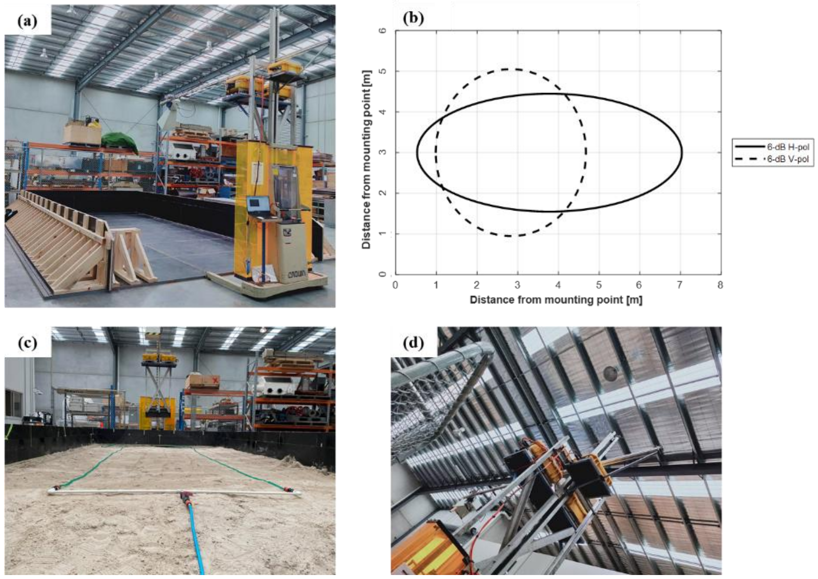

Fig. 1. Picture of the (a) completed soil box with the ELBARA-III mounted on a movable electric hoist, (b) ELBARA-III footprints for H- and V-polarization at 40° incidence angle, (c) sand surface with irrigation system for changing the moisture content, and (d) the roof structure.

and a new internal temperature control. This dual-polarized (vertical and horizontal polarization) antenna has a 3 dB beam width of 31° for measuring TB within the protected frequency band 1.4-1.427 GHz. The estimated elliptical 6 dB footprint for the antenna is based on an installation height of 2.7 m and incidence angle of 40° (Figure 1b). Calibration was performed based on sky and blackbody measurements every experimental day, giving an accuracy of 1K.

This experiment was conducted in a warehouse with a 4 m × 7 m "soil box" containing 200 mm thick sand material (100 % sand) as indicated in Figure 1c. According to prior research, it is anticipated that the medium below 100 mm will not have any major impact on observed TB under the conditions of this experiment [15]. The roof structure of the warehouse consists of interwoven plastic panels, metal panels and steel beams (Figure 1d). The soil box has been sized so as to contain the radiometer footprint at 6 dB (Figure 1b). ELBARA III was mounted on a movable electric host (Figure 1a), such that the horn antenna height above ground level can be adjusted by an electric control and the horn antenna angle changed from 0 to 180°. Hence, ELBARA III was used to provide information on TB at different incidence angles to the soil surface (from 0 to 40° at 5° steps) and of the roof (from 180 to 140° at 5° steps). A laser profiler was used to measure the surface roughness. A total of four Stevens Water Hydra Probes were used to record vertical soil temperature and SM profiles at 50 mm depth increments down to 200 mm. SM was also measured using physical samples taken within the footprint.

The experiment was performed for four moisture contents (SM 1 = 0.02 m^3/m^3, SM 2 = 0.05 m^3/m^3, SM 3 = 0.06 m^3/m^3 and SM 4 = 0.09 m^3/m^3) and 9 incidence angles of the antenna (from 0 to 40 degree at 5° steps). The initial soil moisture condition was 0.02 m^3/m^3 prior to watering with sprinklers to increase the soil moisture. However, because the material used in this experiment was sand, the hydraulic conductivity rate was high, and so it was not possible to sustain moisture contents greater than 0.09 m^3/m^3.

The experimental environment was checked for RFI by measuring the TB of the soil surface and the concrete with ELBARA when the entire building's power (and all of its devices) was turned on and off. No difference was observed confirming that there was no RFI effect on the measurements in this experiment.

III. METHODOLOGY

The total microwave energy emission (the microwave brightness temperature or TB) that is observed by the radiometer can be expressed by the sum of two components as

$$TB_{observed} = TB_{surface} + TB_{enviroment}, \qquad (1)$$

where $TB_{surface}$ and $TB_{enviroment}$ are the TB of the soil surface and the environment background radiation (sky, building, or roof, etc), respectively.

The microwave TB of a soil surface is expressed as the product of the surface temperature and the surface emissivity. Moreover, for outdoor measurement, the TB contribution from the atmosphere or "sky" is typically ignored with $TB_{sky} \simeq 4$ K [16]. Therefore, the TB of an outdoor bare soil surface is related to the physical temperature of the soil (T_{soil}) through the emissivity such that

$$\begin{aligned} TB_{observed} &= (1-r)*T_{soil} + r*TB_{enviroment} \\ &= (1-r)*T_{soil} + r*4 \\ &\simeq (1-r)*T_{soil}, \end{aligned} \qquad (2)$$

where *r* is the soil surface reflectivity.

However, for indoor measurement, the TB of the environment can be much higher than the TB of the sky.

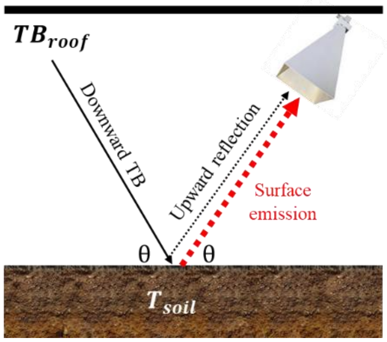

Fig. 2. Indoor microwave radiative transfer concept.

Therefore, the downward TB of the roof in this experiment, propagated down to the soil surface and then reflected and transmitted upwards to the antenna, needs to be considered. Assuming specular reflection theory is applicable [17], the TB from a smooth surface is that from the same incidence angle (θ) as observed by the radiometer as indicated in Figure 2.

In this setup, the TB from the roof (and/or wall etc) provided a substantial contribution to the TB observed by the radiometer. Hence, for indoor measurements such as this, the TB observed from the bare soil surface is related to the physical temperature of the soil (T_{soil}) and TB of the roof/wall (TB_{roof}) through the reflectivity (r) such that

$$\begin{aligned} TB_{observed} &= (1-r)*T_{soil} + r*TB_{enviroment} \\ &= T_{soil} + (TB_{roof} - T_{soil})*r. \end{aligned} \tag{3}$$

Accordingly, a forward model was established to predict TB_{soil} for bare soil in two scenarios. The first was according to Eq. 2 which neglects the environmental contribution. The second was according to Eq. 3 which considers the contribution of the environment. In the second scenario, observations of both TB_{roof} and T_{soil} were used to estimate TB_{soil}. Specifically, the reflectivity (r) was calculated from the soil dielectric constant (obtained from the Dobson model [18] and the incidence angle (θ) using the Fresnel equations ($r = (\varepsilon_s, \theta)$), for the horizontal (H) and vertical (V) polarization [19]. Other parameters required in the model, including soil roughness parameters and the effective soil temperature, were calculated; a detailed description of the equations used in this study can be found in [20]. The $TB_{observed}$ with the environmental contribution data TB_{roof}, collected from ELBARA at a range of angles and moisture contents, was used to evaluate the forward simulation when using Eq. 2 and Eq. 3. SM was subsequently retrieved by iteratively running the forward model to match with the known $TB_{observed}$ from ELBARA according to the cost function from the L-MEB (L-band Microwave Emission of the Biosphere) inversion model [21]. Finally, SM retrieval results using the environmental correction in Eq. 3 is presented and evaluated.

IV. RESULTS AND DISCUSSION

A. Impact of incidence angle on indoor TB observations

The simulated TB of the soil surface using Eq. 2 and Eq. 3 at different angles were estimated and compared to the observation data at the four moisture contents. From the results of Figure 3, the following points were identified:

- Observed data at different angles showed that the value of TB for the surface was about 300 K with no change when changing the incidence angle.
- When using Eq. 2, simulation results provided a TB value ranging from 200 to 270 K, while Eq. 3 provided values of about 300 K, being equivalent to those observed.
- When using Eq. 2 to simulate TB for the surface at different angles, the difference between horizontally and vertically polarized TB increased with increase in incidence angle. The difference was 0 K at 0° and increased to about 40

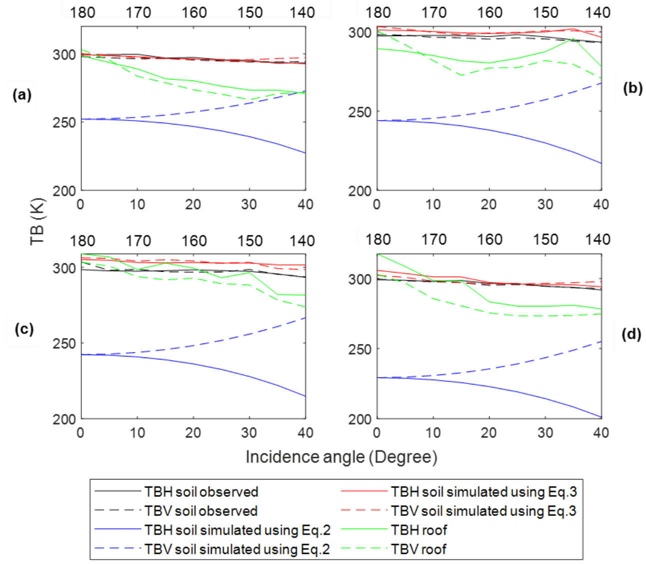

Fig. 3. The TB results at incidence angles ranging from 0 to 40°, including TB observation of the soil surface and the roof from ELBARA, TB simulation of the soil surface when using Eq. 2 and Eq. 3 at (a) SM 1 = 0.02 m^3/m^3, (b) SM 2 = 0.05 m^3/m^3, (c) SM 3 = 0.06 m^3/m^3, and (d) SM 4 = 0.09 m^3/m^3.

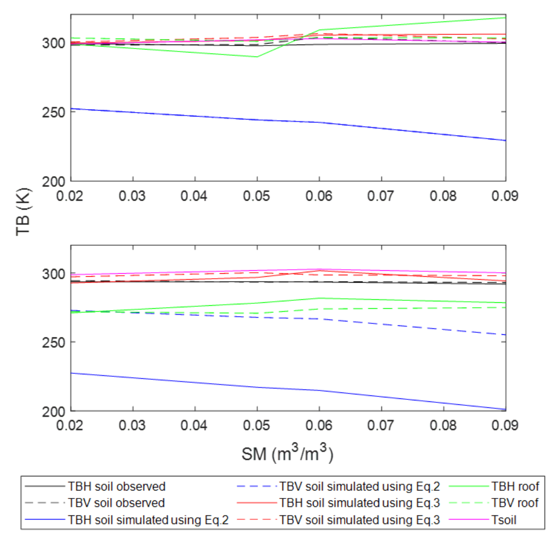

Fig. 4. The effective soil temperature (T_{soil}) and TB values at different moisture contents (from 0.02 to 0.09 m^3/m^3), including observed and simulated TB when using Eq. 2 (blue) and Eq. 3 (red) at 0° (top) and 40° (bottom).

K at 40°. However, the results from observation and simulation using Eq. 3 showed that the TB did not have any difference with angle.

In Figure 3, the TB measurements from the roof appear unstable across different angles due to a variety of reasons, including the influence of other surrounding environmental components (such as walls) at higher incidence angles, the difference in roof structure/ material across the span, and/or the temperature differential between different days.

B. Impact of soil moisture on indoor TB observations

The relative soil dielectric constant for the sand material used in this study was calculated as 5, 7.5, 8.3, and 10.7 for the SM values of SM 1 to SM 4 respectively. The TB simulation of the soil surface using Eq. 2 and Eq. 3 at different moisture contents was estimated and compared to the observation data at 0° and 40°. From the results of Figure 4, the following points were identified:

- Higher SM should lead to a decrease in TB, however, observed TB data showed that the values remained unchanged at around 300 K when changing SM.
- Simulation results from Eq. 2 provided TB values that dropped from 250 K to 230 K when SM increased from 0.02 m^3/m^3 to 0.09 m^3/m^3, while Eq. 3 provided higher values of about 300 K that remained constant at different moisture contents.

C. Improved indoor TB observations and impact on soil moisture retrieval results

The TB comparison of all 36 scenario measurements including at 9 angles from the soil surface under four moisture contents, with simulated values using Eq. 2 and Eq. 3, are plotted in Figure 5. The results showed a substantial improvement in observed and calculated TB when using Eq. 3 (RMSE of 4 K) compared to when using Eq. 2 (RMSE of 57 K), due to the roof effects for indoor measurements.

While Eq. 3 can theoretically be used to retrieve SM from

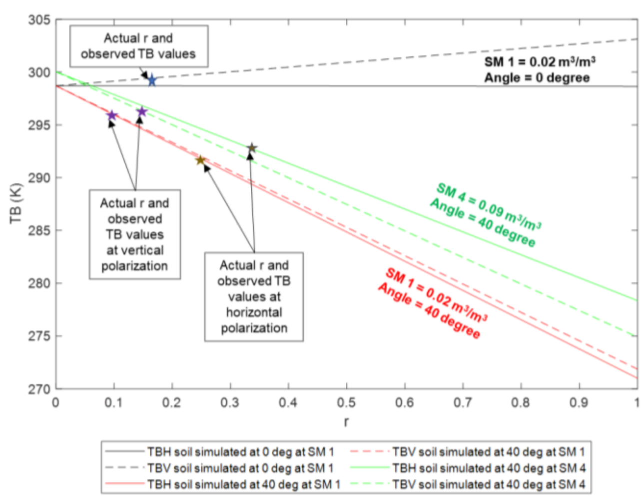

Fig. 6. Examples of the simulated TB observed from the soil surface at different surface reflectivity (r) at 0° and 40° at the first (SM 1 = 0.02 m^3/m^3) and fourth (SM 4 = 0.09 m^3/m^3) moisture conditions (lines) and observations in the experiments (stars).

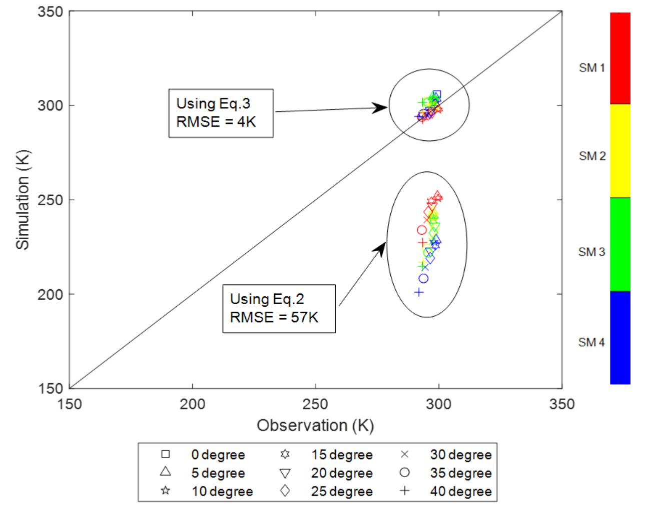

Fig. 5. Comparison of 36 TB measurements at four SM contents (SM 1 = 0.02 m^3/m^3, SM 2 = 0.05 m^3/m^3, SM 3 = 0.06 m^3/m^3 and SM 4 = 0.09 m^3/m^3), and at nine incidence angles (from 0 to 40° at 5° steps). The scatterplot includes observation data compared to simulation using Eq. 2 and Eq. 3.

observations taken indoors, it was found to be impossible based on the data collected in this experiment. For example, the observed TB of the roof for the 0° scenario and the effective soil temperature, were approximately equal; $(TB_{roof} - T_{soil}) \simeq 0$K; Fig. 4 (top). Under these conditions the observed TB of the soil surface from the sensor was approximately the same as the soil temperature ($TB_{observed} \simeq T_{soil}$) at different moisture contents, and so it was impossible to identify the correct value of soil surface reflectivity (r) as any value of r between 0 and 1 gave a similar TB result consistent with the observations (Fig. 6). Similarly, the effective soil temperature and observed TB of the roof were approximately equal at 40° ($(TB_{roof} - T_{soil}) \simeq constant$); (Fig. 4 (bottom)). Thus, the observed TB of the soil surface from the sensor was similar ($TB_{observed} \simeq constant$), despite the different moisture conditions, making it impossible to retrieve the correct value of soil moisture, as different r values from different moisture conditions gave an approximately equal TB result (Fig. 6). Accordingly, the SM could not be retrieved in this experiment.

V. DISCUSSION

By examining the differences of simulated and observed TB with and without correcting for environmental effects, the results of this study have demonstrated that the influence of the indoor environment on passive microwave sensor measurements can be profound. The TB observed from the surface by the radiometer can be much higher than the TB which would be observed in a natural outdoor setting when the contribution of the environmental TB (roof/wall TB in this study) is not considered. The expected TB can be estimated satisfactorily when incorporating this contribution under the assumption of specular reflection; all experiments in this study were performed on a flat sand surface, and so assuming specular conditions was appropriate. This result leads to an expectation that SM can be retrieved from a radiometer measurement indoors. However, the TB from the soil could not be estimated in this experiment, as any changes in reflectivity had an equivalent effect on the total observed TB, meaning that SM retrieval could not be achieved. Accordingly, insights from the results of this study can contribute to further research on indoor radiometer measurement for SM retrieval.

VI. CONCLUSION

Environment brightness temperatures have a substantial influence on indoor measurements resulting in the observed TB, being higher than their actual TB by as much as 57 K. Moreover, under such conditions the observed TB did not change with changes in incidence angles or moisture content. Therefore, the effect of the environmental TB on L-band radiometer measurements must be corrected under such conditions. Theoretically, indoor measurements can be corrected to obtain useful moisture content, as it was shown to reduce the RMSE to only 4 K, but the data collected in this experiment could not be used to satisfactorily retrieve SM information. Future experiments and studies covering different soils, a wider range of moisture conditions, broader array of indoor settings, and utilization of more complex reflection theories need to be performed to confirm the effectiveness of SM retrieval from indoor measurements.

ACKNOWLEDGMENT

The authors would like to thank the reviewers and editors for their grateful comments to improve this manuscript.

The authors would like to thank Pascal Mater, Xiaoling Wu, and Luisa Fernanda White Murillo for their help in testing the experimental equipment and supporting the experiment. The ELBARA III was provided by the Institute of Bio- and Geosciences, Forschungszentrum Jülich GmbH, 52425 Jülich, Germany and other equipment were provided by Prof. Jeff Walker's group.

REFERENCES

[1] A. M. Shutko, "Microwave Radiometry of Lands under Natural and Artificial Moistening," *in IEEE Transactions on Geoscience and Remote Sensing*, vol. GE-20, no. 1, pp. 18-26, Jan. 1982, doi: 10.1109/TGRS.1982.4307514.

[2] Y. H. Kerr, P. Waldteufel, J. -P. Wigneron, J. Martinuzzi, J. Font and M. Berger, "Soil moisture retrieval from space: the Soil Moisture and Ocean Salinity (SMOS) mission," *in IEEE Transactions on Geoscience and Remote Sensing*, vol. 39, no. 8, pp. 1729-1735, Aug. 2001, doi: 10.1109/36.942551.

[3] D. Entekhabi et al., "The Soil Moisture Active Passive (SMAP) Mission," *in Proceedings of the IEEE*, vol. 98, no. 5, pp. 704-716, May 2010, doi: 10.1109/JPROC.2010.2043918.

[4] F. T. Ulaby, M. Razani and M. C. Dobson, "Effects of Vegetation Cover on the Microwave Radiometric Sensitivity to Soil Moisture," *in IEEE Transactions on Geoscience and Remote Sensing*, vol. GE-21, no. 1, pp. 51-61, Jan. 1983, doi: 10.1109/TGRS.1983.350530.

[5] W. E. a. A. Camps, Introduction to satellite remote sensing: atmosphere, ocean, land and cryosphere applications, *Elsevier*, 2017.

[6] P. E. O'NEILL, N. S. CHAUHAN and T. J. JACKSONUSDA/ARS, "Use of active and passive microwave remote sensing for soil moisture estimation through corn," *International Journal of Remote Sensing*, vol. 17, no. 10, pp. 1851-1865, 1996, doi: 10.1080/01431169608948743.

[7] U. Narayan, V. Lakshmi and E. G.Njoku, "Retrieval of soil moisture from passive and active L/S band sensor (PALS) observations during the Soil Moisture Experiment in 2002 (SMEX02)," *Remote Sensing of Environment*, vol. 92, no. 4, pp. 483-496, Sep. 2004, doi: 10.1016/j.rse.2004.05.018.

[8] R. Acevo-Herrera, A. Aguasca, X. Bosch-Lluis and A. Camps, "On the use of compact L-band Dicke radiometer (ARIEL) and UAV for soil moisture and salinity map retrieval: 2008/2009 field experiments," *2009 IEEE International Geoscience and Remote Sensing Symposium*, 2009, pp. IV-729-IV-732, doi: 10.1109/IGARSS.2009.5417480.

[9] X. Wu, J. P. Walker, F. Jonard and N. Ye, "Inter-Comparison of Proximal Near-Surface Soil Moisture Measurement Techniques," *in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 15, pp. 2370-2378, 2022, doi: 10.1109/JSTARS.2022.3156878.

[10] D. A. Houtz, W. Emery, D. Gu and D. K. Walker, "Brightness Temperature Calculation and Uncertainty Propagation for Conical Microwave Blackbody Targets," *in IEEE Transactions on Geoscience and Remote Sensing*, vol. 56, no. 12, pp. 7246-7256, Dec. 2018, doi: 10.1109/TGRS.2018.2849647.

[11] I. R. U. STIG M. LøVAS, "Weather influence on passive microwave brightness temperatures.," *Polar research*, vol. 13, no. 1, pp. 67-81, 1994.

[12] S.-B. D. a. Z.-L. L. Xiao-Jing Han, "Atmospheric correction for retrieving ground brightness temperature at commonly-used passive microwave frequencies," *Optics Express*, vol. 25, no. 4, pp. A36-A57, 2017.

[13] Z. Wei-Chena, H. Zhena, H. Shuang, WangYi-Qing, Z. Xue and WuYi-Shenga, "Characteristics of L-band radio frequency interference detected via the soil moisture active passive radiometer in China and its offshore areas," *Results in Physics*, vol. 12, pp. 1859-1865, 2019, doi: 10.1016/j.rinp.2019.01.062.

[14] C. Matzler et al., "ELBARA, the ETH L-band radiometer for soil-moisture research," IGARSS 2003. *2003 IEEE International Geoscience and Remote Sensing Symposium. Proceedings (IEEE Cat. No.03CH37477), 2003*, pp. 3058-3060 vol.5, doi: 10.1109/IGARSS.2003.1294682.

[15] X. Shen et al., "Soil Moisture Retrieval Depth of P- and L-band Radiometry: Predictions and Observations," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 59, no. 8, pp. 6814-6822, 2020.

[16] T. Pellarin et al., "Two-year global simulation of L-band brightness temperatures over land," *in IEEE Transactions on Geoscience and Remote Sensing*, vol. 41, no. 9, pp. 2135-2139, Sept. 2003, doi: 10.1109/TGRS.2003.815417.

[17] K. E. T. a. E. M. Sparrow, "Theory for off-specular reflection from roughened surfaces," *Journal of the Optical Society of America*, vol. 57, no. 9, pp. 1105-1114, 197.

[18] M. C. Dobson, F. T. Ulaby, M. T. Hallikainen and M. A. El-rayes, "Microwave Dielectric Behavior of Wet Soil-Part II: Dielectric Mixing Models," *in IEEE Transactions on Geoscience and Remote Sensing*, vol. GE-23, no. 1, pp. 35-46, Jan. 1985, doi: 10.1109/TGRS.1985.289498.

[19] A. Fresnel, "Note sur le calcul des teintes que la polarisation développe dans les lames cristallisées," Annales de chimie et physique, 1981.

[20] J.-P. Wigneron, Y. Kerr, P. Waldteufel, K. Saleh, M.-J. Escorihuela, P. Richaume, P. Ferrazzoli, P. de Rosnay, R. Gurney, J.-C. Calv, "L-band microwave emission of the biosphere (L-MEB) model: Description and calibration against experimental data sets over crop fields," *Remote Sensing of Environment*, vol. 107, no. 4, pp. 639-655, 2007, doi: 10.1016/j.rse.2006.10.014.

[21] J.-P Wigneron, J.-C Calvet, T Pellarin, A.A Van de Griend, M Berger, P Ferrazzoli, "Retrieving near-surface soil moisture from microwave radiometric observations: current status and future plans," *Remote Sensing of Environment*, vol. 85, no. 4, pp. 489-506, 2003, doi: 10.1016/S0034-4257(03)00051-8.