Parameterization of the Land Parameter Retrieval Model for L-Band Observations Using the NAFE'05 Data Set

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***Abstract*—The Land Parameter Retrieval Model (LPRM) has been successfully applied to retrieve soil moisture from space-borne passive microwave observations at C-, X-, or Ku-band and high incidence angles (50°–55°). However, LPRM had never been applied to lower angles or to L-band observations. This letter describes the parameterization and performance of LPRM using aircraft and ground data from the National Airborne Field Experiment 2005. This experiment was undertaken in November 2005 in the Goulburn River catchment, which is located in southeastern Australia. It was found that model convergence could only be achieved with a temporally dynamic roughness. The roughness was parameterized according to incidence angle and soil moisture. These findings were integrated in LPRM, resulting in one uniform parameterization for all sites. The parameterized LPRM correlated well with field observations at 5-cm depth ($r = 0.93$ based on all sites) with a negligible bias and an accuracy of 0.06 $m^3 \cdot m^{-3}$. These results demonstrate comparable retrieval accuracies as the official SMOS soil-moisture retrieval algorithm (L-MEB), but without the need for the ancillary data that are required by L-MEB. However, care should be taken when using the proposed dynamic roughness model as it is based on a limited data set, and a more thorough evaluation is necessary to test the validity of this new approach to a wider range of conditions.**

***Index Terms*—L-band radiometry, National Airborne Field Experiment (NAFE), passive microwave remote sensing, soil moisture.**

I. INTRODUCTION

RETRIEVAL of soil moisture from remotely sensed passive microwave observations can be a difficult task because additional information of soil and vegetation characteristics is needed to derive reliable soil moisture from microwave models. Unfortunately, this information is difficult to obtain. In passive microwave radiometry, scientists have been struggling with these issues for a long time. This lack of ancillary data was first acknowledged by Schmugge *et al.* [1] in the 1970s. Consequently, they designed an experiment to estimate soil moisture from aircraft observations with L-, Ku-, and Ka-band microwave radiometers. They discovered the strongest relationship between microwave observations and soil moisture at L-band and addressed the effects frequency, vegetation, roughness, and soil properties on microwave observations. More than 30 years later, soil-moisture remote sensing has evolved, and a series of soil-moisture retrieval models can be found in the literature (see, e.g., [2]–[5]). However, they all use slightly different approaches to describe the soil and vegetation characteristics, which can have a huge effect on the quality of the retrieved soil moisture, particularly at L-band [6]. The Land Parameter Retrieval Model (LPRM) was developed by Owe *et al.* [7] with further developments by De Jeu and Owe [8], Meesters *et al.* [9], Owe *et al.* [3], and De Jeu *et al.* [10]. LPRM uses a radiative transfer model to solve for surface soil moisture and vegetation optical depth simultaneously with a nonlinear iterative optimization procedure. The methodology does not require any field observations of soil moisture or canopy biophysical properties for calibration purposes, and with its limited amount of input parameters, it is specially designed for soil-moisture retrieval from satellite observations. The main difference between LPRM and other soil-moisture retrieval algorithms in the passive microwave domain (see, e.g., [4], [11], and [12]) lies in the way that the vegetation optical depth is derived. Others use either a multifrequency approach [2], [11], a multiangular approach [5], ancillary biophysical data such as the leaf area index [12], or the normalized difference vegetation index [4] to derive the vegetation optical depth, while LPRM uses an analytical solution for the vegetation optical depth using the microwave polarization difference index. This unique approach avoids a reliance on additional vegetation data sets.

In 2007, Wagner *et al.* [13] demonstrated the differences between soil-moisture retrieval approaches by comparing the performance of different models over a monitored study site in Spain. A surprising finding in that study was that both the best and worst results were obtained from two different models that used the same microwave brightness temperature observations. The study clearly showed a poor performance of the official AMSR-E L3 soil-moisture product [11] having no correlation ($r = 0$) with the network of 20 soil-moisture stations at 2–8-cm depth and a good performance of LPRM soil moisture with a correlation coefficient of 0.83. Although this result may be specific for that particular study area, it demonstrated that the retrieval algorithm plays an equally important role in the quality of a derived soil-moisture data set as the technical specifications and performance of the radiometer system [13]. Several studies

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TABLE I
VEGETATION AND SOIL CHARACTERISTICS OF THE EIGHT STUDY SITES.
NB* THE VEGETATION OPTICAL DEPTH VALUES WERE DERIVED FROM LPRM USING THE LIMITED HIGH-ANGLE (> 20°) MICROWAVE OBSERVATIONS

SITE	LAND COVER	TOPOGRAPHY	VEGETATION WATER CONTENT (kg m^{-2}) MEAN (STD)	SAND CONTENT %	CLAY CONTENT %	BULK DENSITY (g cm^{-3})	VEGETATION OPTICAL DEPTH*
Roscommon	Grassland	Flat	0.54 (0.19)	67	15	1.4	0.10
Stanley	Grassland	Sloping	0.26 (0.13)	6	54	1.0	0.28
Dales	Grassland	Sloping	0.45 (0.26)	31	51	0.9	0.36
Midlothian	Fallow / Lucerne	Flat	0.17 (0.08)	10	69	1.2	0.28
Merriwa Park	Wheat	Gently sloping	1.42 (0.39)	21	36	1.1	0.36
Cullingral	Wheat / Barley	Flat	0.54 (0.24)	30	26	1.1	0.38
Illogan	Oats / Barley	Across Gully	0.68 (0.38)	26	23	1.0	0.12
Pembroke	Wheat / Barley	Gently sloping	1.85 (0.89)	6	71	1.2	0.52

(see, e.g., [10], [13], and [14]) have subsequently demonstrated that LPRM [3] is one of the most promising approaches to passive microwave soil-moisture retrieval.

LPRM has been successfully applied to retrieve soil moisture from space-borne passive microwave observations with C-, X-, or Ku-band at high incidence angles (50°–55°). However, until now, it has never been applied to lower angles or to L-band observations, and with the anticipated launch of the first L-band satellite missions (i.e., SMOS, Aquarius, and SMAP), it is important to understand the performance of LPRM for these lower frequency and incidence angles. This letter evaluates LPRM using L-band observations and ground data from the National Airborne Field Experiment 2005 (NAFE'05).

II. MATERIALS AND MODEL

A. Study Area

The NAFE'05 was conducted in the Goulburn River catchment, in southeastern Australia from October 31 to November 25, 2005. The land cover of the catchment included grasslands, crops (wheat, barley, sorghum, and oats), open woodland, and forest, with the last two mainly concentrated in the southern part of the study area. Soil properties in the area are highly variable, including clay soil in the north and sandy soil in the south. The topography in the area is gentle with some flat alluvial areas around the main streams. For this study, eight focus farms within the Goulburn catchment were used. These locations were intensively monitored for top 5-cm soil-moisture and vegetation properties, with each location having different land surface conditions.

A more detailed description of the entire experiment is provided by Panciera *et al.* [15], and only the relevant details for this paper are summarized here (see also Table I).

B. Ground Measurements

The catchment has an extensive network of *in situ* surface and meteorological observations. Soil moisture for the top 5-cm depth was monitored intensively at all these locations. Footprint-average (~62.5 m) soil moisture for each aircraft brightness temperature observation was derived from a very high resolution (~6.25-m spacing) soil-moisture sampling. Given the dense sampling network and the shallow observation (~top 5 cm, which is close to the average measurement depth at L-band [16]), these values were assumed to be representative of remotely sensed soil moisture from the L-band radiometer onboard the aircraft. For each location, 0.25-m^2 biomass samples were also collected on every sampling day to estimate the vegetation biomass and vegetation water content. Footprint-average soil temperature was estimated from the time-series soil temperature recorded at 2.5-cm depth, measured continuously at the nearby monitoring stations, making use of the radiometer time for reference. The effective temperature was provided by the NAFE'05 team using the approach of Wigneron *et al.* [17] which uses soil-temperature data at 2.5- and 15-cm depths, together with top 5-cm soil moisture. The soil properties were determined by analysis of 30-cm-deep soil samples collected at or near the eight permanent monitoring sites.

C. Passive Microwave Observations

During the experiment, the aircraft flew with the polarimetric L-band multibeam radiometer (PLMR). The PLMR measured both V-pol and H-pol brightness temperatures through six cones of approximately 15° beam width with incidence angles between approximately 2° and 44° depending on aircraft attitude. The PLMR was calibrated daily against ground targets (blackbody and clear sky), and the calibration further checked in-flight with overpasses of a nearby water body that was monitored for soil temperature and salinity. The accuracy was estimated to be better than 0.7 K at H-pol and 2 K for V-pol. The calibrated radiometer observations were geolocated, taking into consideration the aircraft position, pitch, roll, and yaw information recorded for each measurement, with the beam centers projected onto a 250-m digital elevation model of the study area. The effective footprint size and ground incidence angles were also calculated, taking into consideration the aircraft altitude, the terrain slope, and beam geometry. Final processing included filtering data corresponding to elevated aircraft roll angles (higher than 10° from horizontal) corresponding to aircraft steep turns. This also minimized the possibility of sun glint in the external beams [18]. Brightness temperature observations at each site were collected during four flights between approximately 9:00 AM and 11:00 AM with a spatial resolution of about 62.5 m.

D. LPRM

LPRM is designed to retrieve soil moisture from dual-polarized brightness temperatures without *a priori* information on vegetation [3]. This model is based on a microwave radiative transfer model that links surface geophysical (e.g., soil moisture, vegetation water content, and soil/canopy temperature) to the observed brightness temperatures [3]. LPRM is a combination of modules to describe the radiative transfer of microwave

TABLE II
MODEL CONFIGURATION OF THE LPRM

MODULE	INPUT PARAMETERS	CALIBRATION PARAMETERS	OUTPUT
Dielectric Mixing Model [27]	Effective Temperature (T_{eff}), Frequency (f), Sand Content (S), Clay Content (C), Bulk Density (BD), (or Wilting Point (WP) and/or Porosity (P)), Soil Moisture (SM)		Dielectric Constant(ε)
Reflectivity Model (Fresnel Law)	Incidence Angle (u), Dielectric Constant (ε)		Smooth surface Reflectivity (r_s)
Roughness Model [22]	Smooth Surface Reflectivity (r_s), Incidence Angle (u)	Roughness (h), Cross Polarization (Q), Roughness Parameters (Nh and Nv)	Rough Surface Reflectivity (r_r)
Vegetation Optical Depth Model [9]	Polarization Ratio ($MPDI$), Incidence Angle (u), Rough Surface Emissivity (e_r)	Single Scattering Albedo (ω)	Vegetation Optical Depth (τ)
Radiative Transfer Model [28]	Effective Temperature (T_{eff}), Canopy Temperature (T_c), Rough Surface Emissivity(e_r), Vegetation Optical Depth (τ)	Single Scattering Albedo (ω)	Brightness Temperature (T_b)

emission from soil and vegetation. Table II gives a summary of these modules. A special characteristic of LPRM is the internal analytical approach to solve for the vegetation optical depth [9]. This unique feature reduces the required vegetation parameters to one, the single scattering albedo. Assuming that the scattering albedo can be considered to be very low (< 0.05) at L-band for low vegetated regions [19] with likely no relationship with polarization [5] and no variation in time [20], this value is assumed to be zero. With this assumption, the LPRM approach does not need additional vegetation information, by using the vegetation information contained in the microwave polarization difference index. Consequently, Table II shows that the parameters requiring calibration are primarily related to the soil roughness. Moreover, several literature studies (see, e.g., [17] and [21]) have demonstrated that it is primarily the roughness parameter (h) that varies from site to site. Finally, LPRM has an atmospheric module, but for these airborne measurements at low altitude, this module was switched off.

This letter mainly focuses on the parameterization of the surface roughness module. Therefore, the rough surface reflectivity (r_r) used in this letter is given according to the study in [22] and is described as

$$r_{r,p1} = [Q \cdot r_{s,p2} + (1 - Q) \cdot r_{s,p1}] \cdot \exp(-h \cdot \cos(u)^{Nrp}) \quad (1)$$

where Q is the polarization mixing factor, subscripts $p1$ and $p2$ are the opposite polarizations (H or V), h is the surface roughness, u is the incidence angle, and Nrp is the exponent. Q can be assumed to be zero at L-band [17]. However, Nrp values can vary, and different combinations of Nrp values were tested. These different combinations had a low impact on the model output (i.e., optical depth and soil moisture), and consequently, Nrp was assumed to be one for both polarizations.

III. PARAMETERIZATION

LPRM was first evaluated with a constant single scattering albedo $(\omega = 0)$ and a fixed roughness model $(h = 0.5, Q = 0)$. These values are consistent with the default parameterization of the L-band Microwave Emission Model over these test sites [23]. The effective temperature was considered to be equal to the canopy temperature, which is a reasonable assumption, particularly for these morning observations. It was found that this model configuration could not capture the observed soil-moisture and vegetation dynamics and did not converge to a stable solution for all different incidence angles. This was due to the predominantly low incidence angle observations and constant roughness assumption. At low angles, the difference between vertical and horizontal polarized brightness temperatures is very small, meaning that the vegetation optical depth could not be resolved from the microwave polarization difference index. In addition, it has been reported that the roughness parameter (h) is not constant at L-band but rather is related to soil moisture and thus varies in time [21], [23].

An optimization routine for the roughness parameter (h) was set up. With the assumption of zero single scattering albedo, zero atmospheric opacity, and the generalization that the effective temperature is equal to the canopy temperature, the radiative transfer model can be rewritten as [24]

$$\frac{T_{b,p}}{T_{\text{eff}}} = 1 - (1 - e_{r,p})\gamma^2 \quad (2)$$

where $T_{b,p}$ is the brightness temperature in kelvins at p (H or V) polarization, e_r is the rough-surface emissivity, T_{eff} is the effective temperature in kelvins, and γ is the vegetation transmissivity. In LPRM, the vegetation transmissivity is assumed to be the same for both polarizations. Equation (2) can then be used to define the horizontal polarized brightness temperature $(T_{b,H})$ as a function of the vertical polarized channel $(T_{b,V})$, effective temperature (T_{eff}), and emissivity (e). Rearranging then yields

$$T_{b,H} = T_{\text{eff}} \left[1 - \left(1 - \frac{T_{b,V}}{T_{\text{eff}}}\right) \frac{(1 - e_{r,H})}{(1 - e_{r,V})}\right]. \quad (3)$$

This equation is now used to optimize roughness (h) using the *in situ* soil moisture for the top 5-cm depth and the estimates of effective temperature as ground truth. The roughness (h) that minimized the rmse between observed and modeled brightness temperatures was determined.

In order to obtain stable solutions, the data points were sorted and binned in 20 clustered intervals between 2° and 44° incidence angles, and one roughness (h) was optimized for each angle group. The derived roughness (h) showed a strong relationship with both incidence angle and soil moisture and can be described with the following simple empirical model:

$$h = 0.4 - sm \cdot u^{1.5} \quad (4)$$

where sm is the soil moisture in cubic meters per cubic meter and u is the incidence angle in radians.

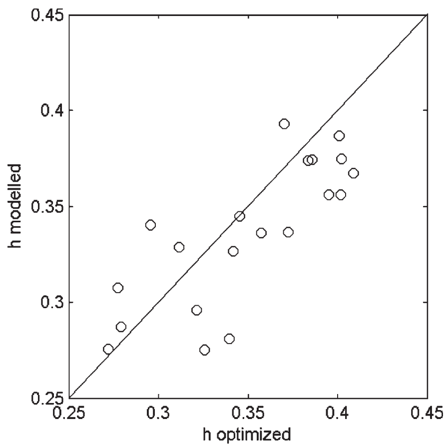

Fig. 1. Scatterplot of the optimized roughness (h) versus the modeled roughness according to (4).

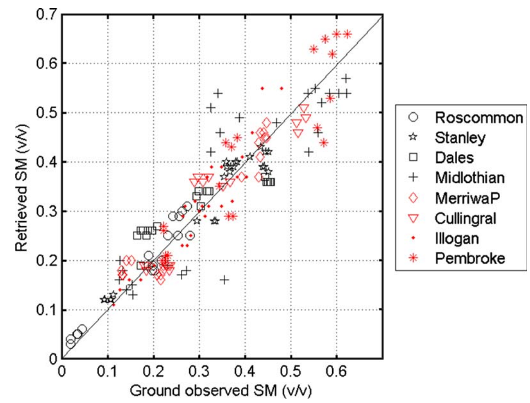

Fig. 2. Evaluation of LPRM soil-moisture (sm) retrieval with ground observations. Red symbols are sites classified as crops, while black symbols are sites classified as grassland. Note that no significant deviation is found between different vegetation types.

In Fig. 1, both modeled and optimized roughness are plotted, showing a high correlation $(r = 0.8)$ between the two for 20 data points. The described roughness–soil-moisture relation of this new model is comparable to other studies and is in line with the microwave theory [21]. The roughness values varied between 0.2 and 0.45 and are lower than the default parameterization of L-MEB $(h = 0.5)$ [23].

The additional relationship with the incidence angle is peculiar and might be an artifact caused by incomplete model physics and/or the limitations of the NAFE'05 data set. A more thorough evaluation is needed to test the validity of this approach. Still, the derived relationship between roughness, soil moisture, and incidence angle [see (4)] was applied in LPRM to study the potential to retrieve soil moisture with a uniform parameterization for all sites.

IV. Results

The individual optical depth values for each site associated with the optimized roughness (h) at high angles $(> 20^\circ)$ were computed. These large angles were selected because LPRM is based on polarization difference, and only at these large angles that the retrieved vegetation optical depth stabilizes. With the limited number of observations at these angles, the retrieved values could only estimate the vegetation optical depth for each site, but the data set was too small to determine the dynamic behavior of this parameter during the entire measuring period. Therefore, the limited retrieved vegetation optical depth values were averaged and assumed to be constant for each site within this four-week time frame.

The resulting vegetation optical depth values for each individual site are presented in Table I. They show the highest value of 0.52 on the wheat and barley field in Pembroke and the lowest values of 0.1 on the grassland in Roscommon and the oat and barley field in Illogan. In the early 1990s, Jackson and O'Neill [24] reported a direct relationship between vegetation optical depth and vegetation water content, and it was suggested that the vegetation optical depth could be written as

$$\tau = b \cdot VWC \tag{5}$$

where b is a constant that depends on the vegetation structure and frequency and VWC is the vegetation water content in kilograms per square meter.

In our case, the retrieved vegetation optical depth compared reasonably well with the observed vegetation water content $(r = 0.6, n = 8)$ when assuming a b value of about 0.3 for all sites. This value is high for L-band frequency (usually about 0.1 for low vegetation [23], [25]). However, the standard deviation of the observed vegetation water content is also very high (particularly at Pembroke, see Table I), and a wrong estimation of this value could easily change the final value of b.

With LPRM adapted to use the new dynamic roughness model [see (4)] and a fixed vegetation optical depth for each site, soil moisture was retrieved at all sites and all angles using only the horizontal polarized brightness temperatures. The performance was then analyzed by comparing the retrieved soil moisture with that observed from ground sampling (see Fig. 2). A uniform solution for all sites was achieved with a correlation coefficient of 0.93, an rmse of 0.055 $m^3 \cdot m^{-3}$, and a negligible bias for the 171 data pairs available. With the exclusion of the worst performing site Midlothian, which was also detected by Panciera *et al.* [23] as being the worst performing site for L-MEB, the accuracy of results increased to a correlation coefficient of 0.94 and an rmse of 0.046 $m^3 \cdot m^{-3}$ (146 data pairs). This degree of accuracy is close to the SMOS soil-moisture target of 0.04 $m^3 \cdot m^{-3}$ [26] and better than the average reported performance of LPRM for C-band observations (~ 0.06 $m^3 \cdot m^{-3}$ [10]). Table III describes the detailed statistics of each individual site. All sites individually had an excellent correlation with the observed soil moisture $(r > 0.9)$, with the exception of Midlothian $(r = 0.86)$. For this study, no significant relation between the performance of LPRM and vegetation cover was found.

V. Discussion and Conclusion

This letter demonstrated the potential use of LPRM for soil-moisture retrieval from L-band microwave observations. LPRM has been successfully used to retrieve soil moisture at satellite scale from C-, X-, and Ku-bands, but it had never been applied to L-band observations. Moreover, it had never been applied to angles below 50°. Consequently, L-band aircraft data at low incidence angles from the NAFE'05 are used to evaluate the performance of LPRM.

It was found that model convergence could only be achieved with a dynamic roughness (h), which was dependent on soil

TABLE III
STATISTICS OF LPRM SOIL-MOISTURE RETRIEVALS FOR EACH SITE. NB* THE SLOPE WAS DERIVED FROM A LINEAR REGRESSION WITH ZERO INTERCEPT

SITE	RMSE ($m^3 m^{-3}$)	CORR. COEF (r)	NUMBER OF OBS. (N)	SLOPE (β)*
Roscommon	0.022	0.98	20	1.04
Stanley	0.032	0.97	23	0.97
Dales	0.069	0.92	18	0.96
Midlothian	0.093	0.86	25	0.96
Merriwa Park	0.040	0.96	21	0.99
Cullingral	0.042	0.94	18	0.98
Illogan	0.039	0.94	26	1.04
Pembroke	0.064	0.92	20	1.01
All	0.055	0.93	171	0.99
All (- Midlothian)	0.046	0.94	146	1.00

moisture and incidence angle. These findings were integrated in LPRM, resulting in one uniform parameterization for all sites. The parameterized LPRM correlated well with field observations at 5-cm depth ($r = 0.93$ based on all sites) with a negligible bias and an average accuracy of 0.055 $m^3 \cdot m^{-3}$. This letter clearly demonstrates the potential of LPRM as it shows comparable retrieval accuracies as the official SMOS soil-moisture retrieval algorithm (L-MEB) with accuracies ranging between 0.013 and 0.074 $m^3 \cdot m^{-3}$ for the eight different locations [23], but without the need for the ancillary data that are required by L-MEB. While it excludes the complex parameterization of the vegetation, a dynamic roughness model had to be included.

Moreover, care should be taken with the dynamic roughness model [see (4)] presented, as the NAFE'05 data set was too small to fully verify the validity of this approach. However, with the anticipated launch of SMOS in 2009, L-band brightness temperatures at different angles will soon be available. With a series of SMOS soil-moisture validation sites and campaigns around the world, the performance of this adapted version of the LPRM can be fully tested.

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