Measurement and Modelling of L-band Forest Emission for Future Soil Moisture Retrieval from SMOS Signatures

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Chapter 6

Summary and Conclusions

6.1 Background

This PhD research project was conducted as part of the background research for the Soil Moisture and Ocean Salinity (SMOS) mission of the European Space Agency (ESA), due for launch in 2009. The main goal of this study was to obtain an improved understanding of L-band (f = 1.4 GHz, λ = 21 cm) forest emission, in view of (SMOS) soil moisture retrievals from heterogeneous pixels containing fractional forest cover. Accurate soil moisture retrievals underneath homogeneous forest canopies are difficult to obtain due to high attenuation by the thick vegetation layer. However, modelling studies showed that in the case of heterogeneous pixels, under certain conditions it was still possible to retrieve an accurate soil moisture content for the non-forested part of the pixel, if forest emission was modelled correctly. Therefore, more detailed knowledge was needed of forest emission at L-band, including an understanding of the radiative transfer properties of the various forest layers and calibration of the forward model to be used in the SMOS soil moisture retrieval algorithm. Existing knowledge on these subjects was rather limited and almost wholly based on modelling studies. It was therefore especially important to obtain additional information from experimental observations. To this end, L-band radiometric data were obtained from tower measurements at the Bray experimental site in Les Landes forest, France in 2004, 2006 and 2007 (BRAY campaigns), and at the Jülich research site, Germany, in 2004 and 2005 (FOSMEX campaigns). The analyses based on these experimental data were used to better understand forest emission and radiative transfer properties. Airborne L-band data were obtained during the NAFE '05 campaign in South-East Australia in 2005. These data were used to investigate the results of soil moisture retrievals from heterogeneous forest pixels.

6.2 Summary and Conclusions

From July-December 2004 the experimental campaign 'Bray 2004' was conducted in the coniferous forest of Les Landes near Bordeaux, France, using a multi-angle L-band radiometer to observe the above-canopy forest emission at horizontal polarization. At the same time, ground measurements were done of soil and litter moisture content, while precipitation was also permanently monitored. This experiment was performed in order to improve the understanding of the L-band signal behaviour over forested areas for different wetness conditions and viewing angles. The greater part of the horizontally polarized L-band signal was found to be dominated by the influence of physical temperature. Variations in soil and/or litter moisture content were visible in the angular signal and in the above-canopy microwave emission, although the dynamic range of this last effect was very small. This, together with the fact that emissivity values were very high, was hypothesized to be due to the presence of a substantial litter layer. However, decoupling of soil and litter effects was difficult because of the strong correlation found between soil and litter moisture.

In a calibration exercise of the L-band Microwave Emission of the Biosphere (L-MEB) model, which is the forward model in the SMOS Level 2 Soil Moisture algorithm, using L-band microwave observations over a coniferous (Pine) and a deciduous (mixed/Beech) forest, litter effects were taken into account by using an 'effective' soil roughness parameter resulting from empirical best-fits. The calibration resulted in working values of the main canopy parameters optical depth (τ_{NAD}), single scattering albedo (ω) and structure parameters tt^H and tt^V, besides the roughness parameters H_R and N_R^P. Using these calibrated values in the forward model resulted in a root mean square error (RMSE) in brightness temperature (T_B) of 2.8 to 3.8 K, depending on data set and polarization, which indicated a good model fit for various moisture conditions. The model parameters showed similar behaviour for both forest types, even though slightly different values were found for each site; notably, coniferous optical depth (0.67) was lower than that of the deciduous site (0.98). A sensitivity study was also conducted for the above parameters, and for temperature, soil moisture and precipitation, to indicate the change in RMSE(T_B) for errors in a given variable. The relationship between canopy optical depth and leaf area index (LAI) was investigated for the deciduous site. Not surprisingly, the correlation was very low, due to the fact that the main contribution to L-band forest emission comes from the branches rather than from the leaves/needles (Ferrazzoli *et al.*, 2002). The results found in this study will be integrated in the operational SMOS Level 2 Soil Moisture retrieval algorithm.

Although the average canopy transmissivity in temperate coniferous and deciduous forests was found to be in the order of 0.4-0.5 (see also Guglielmetti *et al.* (2007, 2008)) and the canopy would therefore be expected to transmit a reasonable amount of ground emission, total emission observed above the canopy showed very little variation with varying soil moisture content, as said above. Moist litter present on the forest floor is known to obscure the soil emission and was hypothesized to be responsible for the small sensitivity in above-canopy emission found during Bray 2004. More knowledge on the L-band radiative properties of litter and understory layers was therefore needed to better understand the emission of the whole forest system.
In order to contribute toward this issue, an additional field experiment at the Bray site was conducted in 2007. Radiometric observations were done of the canopy and of different configurations of the forest floor, following sequential stripping of each forest floor layer. In combination with the long-term data set of above-canopy observations from 2004, this resulted in emissivity values of bare soil, soil-litter, soil-litter-grass and soil-litter-grass-canopy configurations for a range of soil and litter moisture values. Calculations involved the use of the Wilheit and L-MEB models, and a modified version of the approach presented by Schwank *et al.* (2008). The sensitivity to soil moisture was found to be substantially suppressed by the presence of a grass understory and litter. This corroborated the low correlation between soil moisture and above-canopy L-band emission. A detailed sensitivity analysis showed the effects of moisture content and litter layer thickness on the thermal sampling depth and emission of a soil-litter forest floor configuration. Several results of recent modelling and laboratory studies were confirmed by this study, which was to our knowledge the first to use *in situ* experimental data in this context.

Finally, airborne L-band data from the Australian National Airborne Field Experiment 2005 (NAFE '05) field campaign were used to investigate the influence of fractional forest cover on soil moisture retrievals from heterogeneous (grass/forest) pixels. This study was, to our knowledge, the first to use experimental data on this subject and was done in view of the upcoming SMOS mission, in order to contribute to calibration/validation studies and the analysis of heterogeneous land surfaces. Because the multi-angle observations were 'contained' in swaths, swaths were used instead of pixels as the basic surface unit in this study. Simultaneous retrievals of soil moisture (*SM*) and vegetation optical depth were done by inversion of the L-MEB zero-order radiative transfer model. This was done for two different retrieval configurations, the first consisting of swath-effective values of *SM* and τ_{NAD} and the second consisting of values of *SM* and τ_{NAD} for the non-forested (i.e. grass) fraction of the swath, with forest emission known from forward modelling. Model inputs for non-retrieved parameters were either default values taken from the literature or site- and time-specific values obtained from observations of nearby homogeneous swaths gathered during the same flight. The main focus of this study was on retrieval behaviour for various soil moisture conditions and forest fractions. Area-averaged retrieval results were generally very reasonable for both retrieval configurations. When retrieving swath-effective values of *SM* and τ_{NAD}, τ_{NAD} showed an increased overestimation with increased forest fraction. Highest retrieved values of *SM* were found at intermediate values of forest fraction. The results indicate the difficulty in flagging upper limits of pixel forest fraction during soil moisture retrievals, besides showing that erroneous parameter values can lead to high errors in retrieved *SM*, especially in wet conditions. This study is the first to give a realistic idea of the errors and uncertainties involved in soil moisture retrievals from partly forested swaths, and as such is expected to contribute to a better understanding of SMOS calibration/validation issues.

To summarize, this study has given some insight into the general applicability, uses and limitations of the L-MEB model in the case of forests. A model calibration has been performed over two general forest types, forest radiative transfer properties have been investigated and a better understanding has been obtained of the separate contributions of each forest layer to the total above-canopy forest emission. The high emissivity and low sensitivity to ground moisture found in above-canopy forest observations have been demonstrated and could be explained. An indication has been given regarding the feasibility of soil moisture retrievals underneath (partly) forested areas. In conclusion, a better understanding of forest L-band emission in view of soil moisture retrievals over partly forested pixels has been obtained. The fact that forest emission is relatively invariable over a range of moisture conditions may actually be an asset in soil moisture retrievals over heterogeneous pixels, as it facilitates correct emission modelling of the forested part of the pixel.

6.3 Recommendations for Future Research

This thesis only covers a very small part of the subject 'microwave forest emission' and many interesting aspects still remain open for future investigation, while the availability of global-scale SMOS observations will present a wealth of new research opportunities.

The L-MEB model was chosen for the SMOS mission as it is a simple model and thus particularly well suited to global-scale studies. Understandably, it is necessary to make certain assumptions concerning the model components and parameter values in order to deliver a global scale soil moisture product (i.e. a SMOS Level 2 end product). Where possible, default values of the L-MEB parameters should be determined at the satellite scale by model inversion using actual SMOS data. Furthermore, in the case of local or regional scale studies in which field measurements are available, a preferred approach for informed users might be to retrieve soil emission from the SMOS Level 1 brightness temperatures, rather than soil moisture, and then convert soil emission into soil moisture content using site-specific model inputs. Through the use of site-specific information, errors resulting from an imperfect choice of dielectric mixing model, soil texture properties and roughness values can be reduced. The availability of field measurements of soil properties thus allows for a more informed choice of model components and parameter values rather than mere defaults, and the former will in turn result in more correct values of soil moisture. A comparison of results from both approaches, i.e. direct retrieval of soil moisture and retrieval of soil emission followed by conversion into soil moisture, seems a very useful study in the context of SMOS. This also highlights the necessity of a comparison of the performance of various dielectric mixing models for different soil types and moisture conditions.

Besides studies based on the use of L-MEB, at a local scale it remains important to also use multiple-scattering models for the analysis of experimental forest observations, in order to obtain an optimal understanding of L-band forest emission characteristics. It has been shown (Mätzler *et al.*, 2006) that if a truly detailed physical understanding of forest emission characteristics and radiative transfer properties is required, a multiple-scattering model will give the most physically correct results.

Once SMOS data become available, it will be extremely interesting to investigate the relationships between the L-MEB canopy parameters τ, ω and tt^P and forest characteristics such as vegetation species, structure and density. If such differentiation is possible, it could prove a very useful link between SMOS observations and ecological and/or allometric studies. Furthermore, changes in the above parameters with different conditions of internal and external water content should be investigated.

At global and local scales, the relationship between optical depth and vegetation water content is an essential subject for further investigation, requiring both experimental and modelling studies. With the exception of a study by Ferrazzoli *et al.* (2002), existing analyses of this relationship mainly use the so-called '*b*-parameter' and almost exclusively concern grass and crops rather than woody biomass. Coupling of L-band forest observations with soil-vegetation-atmosphere transfer (SVAT) models is expected to aid global-scale monitoring of vegetation water content, and, ultimately, contribute to climate and drought forecasting.

It should be clear from the work presented in this thesis that, although the results are encouraging, modelling L-band forest emission remains a very challenging issue. There are still many gaps in our knowledge that need to be filled, and for this field experiments are essential, especially during the operational phase of SMOS. This thesis thus presents a strong argument to continue this line of research. Given the fact that forests constitute a major land cover type on a global scale, a continuation of this research will undoubtedly increase the potential of the SMOS mission to improve our understanding of the relationships between forest ecosystems and climate events.