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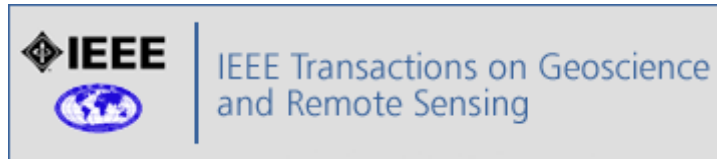
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**L-Band Radiative Properties of Vine Vegetation at the SMOS
Cal/Val Site MELBEX III**

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Review

L-Band Radiative Properties of Vine Vegetation at the SMOS Cal/Val Site MELBEX III

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Abstract

Radiative properties at 1.4 GHz of vine vegetation were investigated by measuring brightness temperatures with the L-band radiometer ELBARA II operated on a tower at the MELBEX III field site in Spain. A reflecting foil was placed under the vines in their winter and summer states to measure brightness temperatures at horizontal and vertical polarization, which provide prevailing information on vegetation transmissivities. The latter were retrieved from dual-polarized brightness temperatures measured at observation angles between 30° and 60° using a multiple scattering radiative transfer model. The analysis revealed practical parameter values that could be used to account for the impact of vine vegetation. The values are representative for the Mediterranean SMOS anchor station, and therefore valuable for the corresponding calibration and validation activities. Likewise, quantifying the uncertainties of the brightness temperatures measured was also important, especially as several equivalent ELBARA II instruments are currently operative in ongoing SMOS-related field campaigns.

1. Introduction

The terrestrial surface layer is an important boundary that controls energy and mass fluxes between the earth's surface and the atmosphere. Techniques for monitoring the surface moisture are therefore of particular interest. Microwave radiometry at L band (1 – 2 GHz) is a passive remote sensing technique applicable for soil moisture retrieval at large scales [1-4]. On

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23 2nd November 2009 the **Soil Moisture and Ocean Salinity** (SMOS) satellite [5, 6] was launched as
24 the **European Space Agency's** (ESA) second Earth Explorer Opportunity mission. The satellite
25 carries the **Microwave Imaging Radiometer using Aperture Synthesis** (MIRAS) [7] on board to
26 provide L-band brightness temperatures $T_B^{p,\alpha}$ at horizontal ($p = H$) and vertical ($p = V$)
27 polarization at multiple observation angles α , with a spatial resolution of approximately $40 \times$
28 40 km^2 and near-global coverage. One of the primary goals of the SMOS mission is to produce
29 global soil moisture maps with an accuracy better than 4 vol-% and a revisit time of less than
30 three days [8]. The reliability of these land surface retrievals depends largely on the performance
31 of the microwave emission models used to retrieve soil surface moisture from the multi-angular
32 $T_B^{p,\alpha}$ measurements. Performing ground-based radiometer campaigns throughout the operative
33 phase of the SMOS mission is therefore essential to validate and further improve the inversion
34 algorithms based on radiative transfer modeling.

35 The **Valencia Anchor Station** (VAS) in Spain was selected as the Mediterranean validation site
36 for the SMOS-based retrievals of soil surface moisture and radiative properties of vegetation.
37 These retrievals are routinely derived from $T_B^{p,\alpha}$, with an inversion scheme based on the τ - ω
38 model that is the zero-order non-coherent solution of the radiative transfer equations [9]. It has
39 been demonstrated that this model is adequate to reproduce $T_B^{p,\alpha}$ at L band (vacuum wavelength
40 of $\approx 21 \text{ cm}$) emitted from vegetated sites [10-14], which makes it suitable for use in a multi-
41 parameter inversion algorithm at feasible computational costs [13, 15, 16]. These findings,
42 together with continuous refinements of the parameterization based on field experiments and
43 simulations (e.g. [17-26]), led to the **L-band Microwave Emission of the Biosphere** (L-MEB)
44 inversion scheme [27], which is the current level-2 processor used to simultaneously derive soil
45 moisture and vegetation opacity from multi-angular SMOS observations $T_B^{p,\alpha}$. However, some of
46 the model parameters involved affect $T_B^{p,\alpha}$ rather similarly, which leads to some ambiguity in
47 retrieving these parameters from L-MEB inversion using SMOS data. To overcome this problem,
48 one option is to perform ground-based L-band radiometer campaigns under well-controlled

1 49 conditions, which yield $T_B^{p,\alpha}$ that are no longer simultaneously affected by some of these
2
3 50 parameters.

4
5 51 Such a setup was used at the **Mediterranean Ecosystem L-Band characterisation EXperiment**
6
7
8 52 **III** (MELBEX III) field site at the Finca El Renegado, Caudete de las Fuentes (Valencia) Spain,
9
10 53 which is fairly homogeneously covered with vineyards. Vineyards constitute approximately 75 %
11
12 54 of the land use at the VAS which includes the MELBEX III site. While measuring the multi-
13
14 55 angular $T_B^{p,\alpha}$ with the tower-based **ETH L-BAnd RAdiometer II** (ELBARA II), a reflecting foil was
15
16 56 placed underneath the vines to ensure that the sensitivity of the measurements to the emission
17
18 57 of the soil below was very low. The $T_B^{p,\alpha}$ derived from these foil experiments were, therefore,
19
20 58 predominantly affected by the vegetation, which meant it was possible to characterize the
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22 59 radiative properties of the vines in different development states. Such information is important for
23
24 60 the ongoing SMOS calibration and validation activities at the VAS because: i) vegetation
25
26 61 parameters retrieved with L-MEB from the $T_B^{p,\alpha}$ provided by the overflying MIRAS radiometer on
27
28 62 board the SMOS satellite can be validated with the “ground truth” vegetation parameters derived
29
30 63 from the ground-based measurements during foil experiments; ii) the “ground truth” vegetation
31
32 64 parameters determined for the MELBEX III field site can be used in L-MEB to improve (or
33
34 65 investigate) the accuracy of SMOS soil moisture retrievals for the VAS.
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41 66 A further motivation for this study was to describe the MELBEX III site (Sections 2.1 and 2.2),
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43 67 and to investigate the long term performance of the ELBARA II radiometer deployed (Section
44
45 68 2.3). Since the MELBEX III site is an important anchor station for the SMOS mission, and since
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47 69 further identical ELBARA II instruments are currently deployed in other SMOS relevant
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49 70 campaigns, the analysis of a first long time series of tower-based $T_B^{p,\alpha}$ measurements is relevant
50
51 71 because: i) the calibration strategy applied to produce the ground-based $T_B^{p,\alpha}$ must be analyzed
52
53 72 and refined according to the findings; ii) uncertainties $\Delta T_B^{p,\alpha}$ of the calibrated $T_B^{p,\alpha}$ must be
54
55 73 quantified so that they can be used for the SMOS validation. A detailed description of the foil
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57 74 experiments carried out to retrieve vegetation radiative properties was presented in Section 2.4.
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1 75 In Section 3.1 the uncertainties $\Delta T_B^{p,\alpha}$ of $T_B^{p,\alpha}$ were estimated so that they could be taken into
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3 76 account in future SMOS calibration and validation activities based on ELBARA II. These
4
5 77 uncertainties constrain the errors in the vegetation radiative properties derived from the
6
7 78 measurements during the foil experiments (Section 3.2). Section 4 describes the derivation of the
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9 79 vegetation radiative properties from the multi-angular $T_B^{p,\alpha}$ and the air temperatures T_{air}
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11 80 measured during foil experiments on the basis of a multiple scattering radiative transfer model.
12
13 81 The resulting retrievals of vegetation transmissivities and optical depths for distinctly different
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15 82 developmental states of the vines are presented in Section 5, and a summary and conclusions
16
17 83 are given in Section 6.
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23

24 84 **2. The MELBEX III experiment**

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26 85 Here the MELBEX III field site for the study is described and a sketch of the auxiliary “ground
27
28 86 truth” information available for the site is given. Although these data were not used in this
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30 87 analysis, they were included to provide a reference for the MELBEX III campaign, since this
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32 88 campaign plays a cardinal role in the ongoing SMOS calibration and validation activities. For the
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34 89 same reason the remote sensing system used is described rather extensively in Section 2.3, as
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36 90 is the setup of the foil experiments (Section 2.4) performed to derive L-band vegetation radiative
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38 91 properties.
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44 92 **2.1. General set-up**

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46 93 The VAS site is located about 80 km west of the city of Valencia (Spain) on the Utiel-Requena
47
48 94 Plateau at 813 m a.s.l.. It was selected by the SMOS science team for the calibration and
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50 95 validation of SMOS data for the Mediterranean area as the landscape is relatively homogeneous
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52 96 over about $50 \times 50 \text{ km}^2$, which is large enough to include at least one SMOS pixel. The
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54 97 predominant land-use types are vineyards (75%) and other Mediterranean ecosystem species
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56 98 such as shrubs, olive and almond trees, and pine forests. The topography is generally flat (slope
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58 99 angle $< 2\%$), with some slightly undulating regions (8% - 15%). The surface air temperature
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60

1 100 ranges from -15 °C in winter to 45 °C in summer, with an annual mean temperature of 14 °C. The
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3 101 mean annual precipitation is about 450 mm, with peaks in spring and autumn.

4
5 102 The passive L-band measurements used in this study were performed at the MELBEX III site,
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7
8 103 which is part of the VAS. The data measured allow soil surface moisture and vegetation
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10 104 parameters to be upscaled for the entire VAS area for comparison with L-MEB retrievals based
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12 105 on SMOS data. In particular, dedicated short-term experiments were performed in which soil
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14
15 106 emission was largely shielded by means of a reflecting foil placed underneath the vine vegetation
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17 107 (referred to as “foil experiments”) to measure $T_B^{p,\alpha}$, which mainly carries information on
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19
20 108 vegetation radiative properties.

21
22 109 Figure 1a shows the ELBARA II radiometer mounted on the tower during a foil experiment,
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24
25 110 with a corresponding sketch in a bird’s eye view in panel b). The distances between the vines
26
27 111 within a row were 2.00 – 2.10 m, and between rows 2.90 – 3.00 m. The MELBEX III vineyard
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29 112 studied belongs to the typical Spanish “tempranillo” variety and is representative of the entire
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31
32 113 VAS area. Panel c) is a photo of the site during the foil experiment in winter and panel d) in
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34 114 summer when the vegetation was fully developed. In the winter state, the vines are heavily
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36 115 trimmed to keep just the stocks with main branches fixed to wires along the rows. Typically, the
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38
39 116 first leaves start appearing at the beginning of May, and grape harvesting begins in the last week
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41 117 of September. Several field campaigns were performed to measure the **Leaf Area Index (LAI)** of
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43
44 118 the developed vines and to determine the effective column densities of the **Volumetric Water**
45
46 119 **Contents (VWC)** of different vegetation elements (stocks, grapes, stems, leaves). These values
47
48 120 are given and used in Section 5.2 to derive estimates of effective vegetation radiative properties,
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50
51 121 which were compared with corresponding remotely sensed values.

52
53 122 Since the installation of the L-band radiometer ELBARA II [28] in September 2009 at the
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55 123 MELBEX III site, brightness temperatures $T_B^{p,\alpha}$ at polarization $p = H, V$ and incidence angles 30°
56
57
58 124 $\leq \alpha \leq 70^\circ$ have been measured automatically in steps of 5° every 30 minutes. In contrast, at $\alpha =$
59
60 125 45° , $T_B^{p,\alpha}$ are recorded every 10 minutes. Simultaneously with each $T_B^{p,\alpha}$ measurement, air
126 temperature T_{air} is recorded right next to the radiometer to provide the only physical temperature

used in our analysis. Furthermore, every day around midnight sky radiances T_{sky} are measured at the nadir angle $\alpha_{\text{sky}} = 150^\circ$ to recalibrate the ELBARA II Active Cold noise Source (ACS) used for internal calibration.

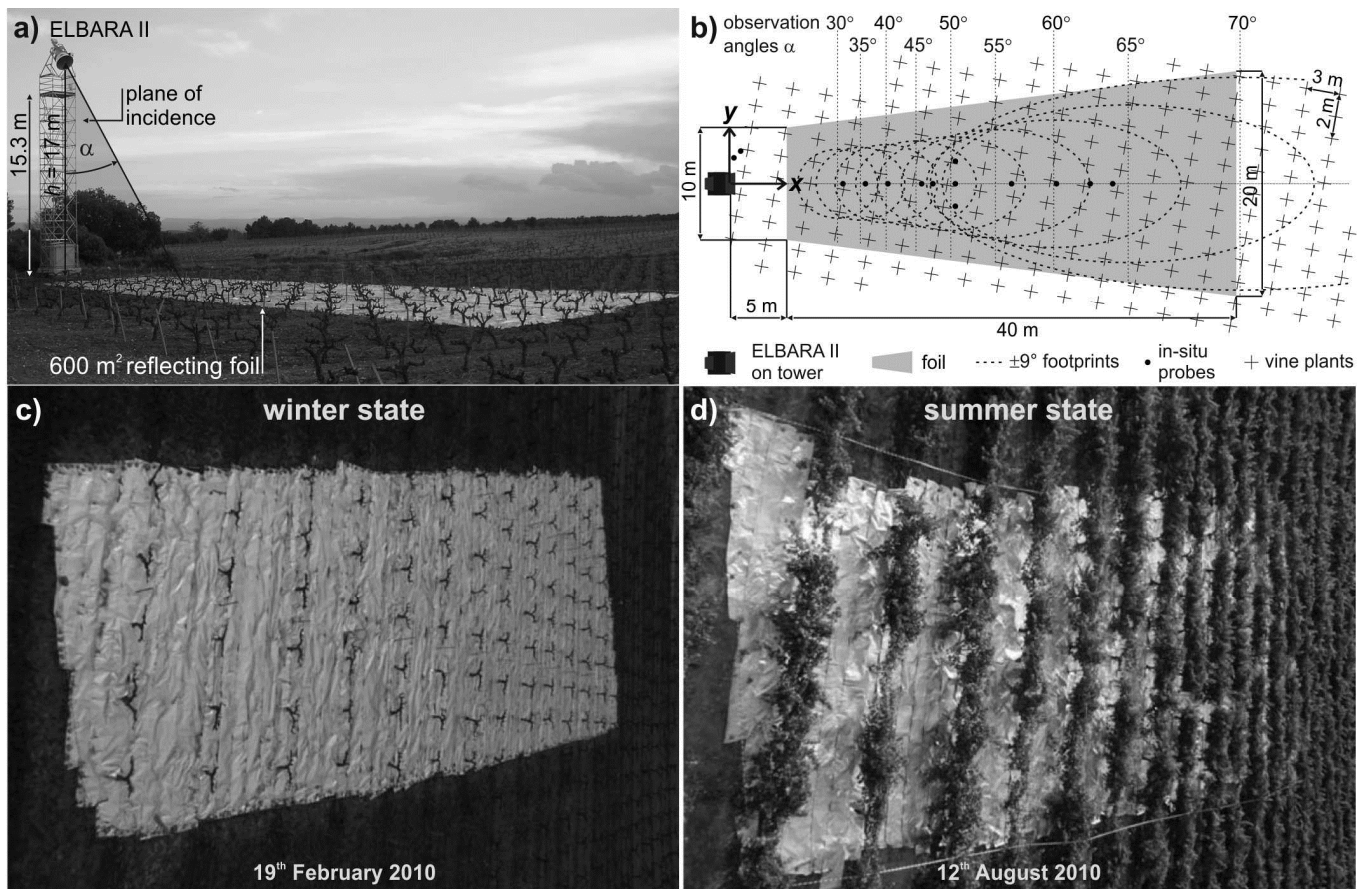


Figure 1: a) Picture of the MELBEX III site during a foil experiment with the L-band radiometer ELBARA II mounted on the tower. b) Bird's eye view of the configuration used in the foil experiments. Bold dots indicate the locations of the in-situ soil measurements, crosses the individual vines, and dashed ellipses the footprints observed at the different elevation angles α . c) and d) Photos of the sites prepared to investigate the winter state of the vegetation and its fully developed summer state on the basis of the $T_B^{p,\alpha}$ measured.

2.2. Auxiliary data

The following auxiliary "ground truth" information is available for the MELBEX III site and relevant for the ongoing SMOS calibration and validation activities at the VAS area.

i) Time-series of precipitation measured every 15 minutes are available from the Jucar River Basin Authority rain gauge approximately 2 km from the MELBEX III site. Complementary meteorological data with a temporal resolution of 10 minutes are available from the VAS meteorological station situated at the Finca Cañada Honda, Bodegas Iranzo, about 4 km from the MELBEX III site.

1 138 ii) Soil moisture within the topmost 6 cm is measured in-situ every 10 minutes within the
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3 139 ELBARA II footprints using capacitive ThetaProbes (Delta-T Devices Ltd., type ML2x, nominal
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5 140 accuracy $\pm 1\%$). To acquire surface soil moisture representative of the ELBARA II footprints,
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8 141 probes were installed on bare soil between vine rows and underneath the vines, close to the
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10 142 stumps (black dots in Figure 1b). Site-specific calibration was used to derive volumetric moisture
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12
13 143 from raw sensor data.

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15 144 iii) Next to the tower base, a small network of additional moisture and temperature probes was
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17 145 installed (ThetaProbes; a Profile Probe, Delta-T Devices Ltd., type PR2) to monitor soil moisture
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19
20 146 at 4 depths down to 80 cm, and LI-COR sensors to measure soil temperatures at the depths 5,
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22 147 10, 20, 30, 50 and 80 cm below the ground.

23
24 148 iv) A compact DAVIS Vantage Pro meteorological station is attached to the ELBARA II tower
25
26
27 149 2 m above ground to monitor air temperature, atmospheric humidity, pressure, wind speed and
28
29 150 wind direction every 10 minutes.

31 32 33 151 **2.3. Remote sensing system**

34
35 152 The L-band radiometer ELBARA II [28] deployed at the MELBEX III site is the successor of the
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37
38 153 **ETH L-BAnd RA**diometer for soil-moisture research (ELBARA) [29], designed and built by the
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40 154 Institute of Applied Physics, University of Berne, Switzerland. Since further ground-based
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42 155 radiometer campaigns during the SMOS commissioning phase and during the operative phase of
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44
45 156 the mission appeared to be needed, three identical ELBARA II radiometer systems were
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47 157 requested by ESA and currently operative in SMOS relevant field campaigns.

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49 158 ELBARA II was designed to be sensitive within the protected part 1400–1427 MHz of the
50
51
52 159 microwave L band (1000–2000 MHz). Since the receiver bandwidth $B \approx 22$ MHz (at -3 dB) was
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54 160 narrow, the received noise power emitted from a site at the physical temperature $T \approx 300$ K may
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56
57 161 be as low as $P = k \cdot T \cdot B \approx 10^{-13}$ W. Low-noise amplifiers and a series of passive components with
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59 162 the net gain of 69 dB were implemented in the ELBARA II **Microwave Assembly (MA)**. This was
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163 required to amplify the low input power to a level that matches the operational range of the power

detector used, so that voltages U could be generated at the output of the **Power Detector Assembly (PDA)** as linear responses to the input noise power. Furthermore, a sophisticated thermal system was developed to ensure the thermal stabilization of the electronics was accurate as this is crucial for long-term applications under widely varying environmental conditions.

Another challenge for the ELBARA II design was the internal calibration to derive $T_B^{p,\alpha}$ from instrumental raw data. This was solved by periodically switching between different reference noise sources fed to the radiometer MA, while recording the responses U at the output of the PDA. A **Resistive noise Source (RS)** stabilized at the temperature $T_{RS} > T_B^{p,\alpha}$ was used for the hot calibration source, yielding the reference response U_{RS} at the PDA. The implementation of an **Active Cold Source (ACS)** to generate a cold reference noise temperature $T_{ACS} < T_B^{p,\alpha}$ with the associated PDA response U_{ACS} was another of the innovations implemented in ELBARA II. The noise temperature $T_{RM,in}^p$ at the radiometer input ports for H- and V-polarization were derived from the associated responses U^p using the linear interpolation between the reference responses of the RS and the ACS with known noise temperatures of $T_{ACS} \approx 37.8$ K and $T_{RS} \approx 313$ K (see subsection a) below).

$$T_{RM,in}^p = \frac{T_{RS} - T_{ACS}}{U_{RS} - U_{ACS}} (U^p - U_{ACS}) + T_{ACS} \quad \text{and} \quad T_B^{p,\alpha} = \frac{T_{RM,in}^p - (1 - t_{FC}) T_{FC}}{t_{FC}} \quad (1)$$

However, the experimentally relevant $T_B^{p,\alpha}$ entering the antenna aperture was slightly smaller than $T_{RM,in}^p$ due to the noise added by the lossy **Feed-Cable (FC)** with transmissivity $t_{FC} < 1$. This was taken into account in the second equation in (1) that corrects $T_{RM,in}^p$ for the noise added by the FC at the temperature T_{FC} . To avoid error-prone extrapolation in deriving $T_{RM,in}^p$ from (1), the noise levels of the internal calibration sources were designed to fulfill $T_{RS} > T_{RM,in}^p > T_{ACS}$, which significantly increased the absolute accuracy of $T_{RM,in}^p$.

The technical details for the ELBARA II system are given in [28], but the specific system performances, which are important from the experimental point of view, are described in the

1 188 following subsections, drawing on experience in the field during the MELBEX III campaign. They
 2
 3 189 are important for the harmonized operation of the different ELBARA II systems currently in use.
 4
 5

6 190 *a) Noise reference sources*
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8
 9 191 A 50Ω RS stabilized at the instrument set-point temperature $T_0 = 40 \text{ }^\circ\text{C}$ was used to provide
 10
 11 192 the reference noise temperature $T_{\text{RS}} = T_0$ measured for the RS. For the time period from 19th
 12
 13 193 February 2010 to 1st February 2011, the mean RS temperature was $T_{\text{RS}} = 40 \text{ }^\circ\text{C} = 313.15 \text{ K}$, with
 14
 15
 16 194 a standard deviation of $\sigma T_{\text{RS}} < 0.08 \text{ K}$, and the mean system response was $U_{\text{RS}} = 1.1089 \text{ V}$, with
 17
 18 195 a standard deviation of $\sigma U_{\text{RS}} < 0.0002 \text{ V}$.
 19

20
 21 196 Since long-term experience with the novel ACS was lacking, diurnal recalibration at around
 22
 23 197 midnight was needed using sky measurements where $T_{\text{sky}} < T_{\text{ACS}}$ and measurements on the RS
 24
 25 198 where $T_{\text{RS}} > T_{\text{ACS}}$ (Section 3.1.4 in [28]). The ACS reference noise T_{ACS} was determined
 26
 27
 28 199 analogous to (1) (see Section 3.1.4 in [28]) with sky radiance T_{sky} computed with [30] for the
 29
 30 200 elevation 750 m a.s.l. of the MELBEX III site and T_{air} measured. The mean T_{ACS} determined for
 31
 32 201 the experimental time period was $T_{\text{ACS}} = 37.83 \text{ K}$, with a standard deviation of $\sigma T_{\text{ACS}} = 0.63 \text{ K}$.
 33
 34
 35 202 The associated mean system response was $U_{\text{ACS}} = 0.4711 \text{ V}$, with a standard deviation of
 36
 37 203 $\sigma U_{\text{ACS}} < 0.0001 \text{ V}$. These observations indicate that the thermal stabilization of ELBARA II was
 38
 39
 40 204 excellent when it was operated under environmental conditions with air temperatures ranging
 41
 42 205 from $-3 \text{ }^\circ\text{C} < T_{\text{air}} < 35 \text{ }^\circ\text{C}$. They also imply that the ACS is stabil in the long term, which allows
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 44
 45 206 significantly longer cycles to be applied for the recalibration of the ACS with sky measurements.
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47
 48 207 *b) Treatment of radio frequency interferences*
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50 208 **Radio Frequency Interference (RFI)** can occur even within the protected 1400–1427 MHz
 51
 52 209 band, which is the sensitive frequency range of ELBARA II. Hence, RFI was reduced by narrow-
 53
 54
 55 210 band filtering at the radiometer input (before amplification). Two strategies were used to detect
 56
 57 211 RFI: (i) **Narrow-band continuous RFI** was detected by splitting the protected band into a **Lower**
 58
 59 212 **Side Band (LSB)** and an **Upper Side Band (USB)**. The **Frequency-Domain (FD)** criterion
 60

213 $FD \equiv |T_{\text{B,USB}}^p - T_{\text{B,LSB}}^p|$, with a threshold $FD = 0.4 \text{ K}$, was used to detect narrow-band RFI. (ii) Bursts

of RFI were detected by analyzing the time series of noise power measured at the rate of 800 Hz. It was expected that the inherent Gaussian statistics associated with undisturbed thermal noise would be altered by RFI bursts, so that these bursts could be detected by checking kurtosis k [31, 32], which is $k = 3$ for a perfect Gaussian distribution. Consequently, the Time-Domain (TD) criterion $TD \equiv |k - 3|$ was defined to identify RFI bursts. The corresponding threshold value was determined on the basis of the responses U_{RS} measured at the PDA output, when the internal RS was switched to the receiver path. As expected, the kurtosis of these undisturbed measurements was $k_{RS} = 3$, with a standard deviation $\sigma k_{RS} < 0.1$. This value is considered as the instrumental limitation, which led us to set the threshold to $TD = 3 \cdot \sigma k_{RS} \approx 0.3$ for the antenna measurements.

c) Antenna and radiometer mount

The ELBARA II system is mounted on a tower 15.3 m above the ground (Figure 1a). The system is equipped with an elevation tracker that allows the antenna to be oriented automatically for $30^\circ \leq \alpha \leq 330^\circ$ with $\alpha = 180^\circ$ as the zenith direction (Section 2.4. in [28]). After the system was installed on the tower, the elevation tracker was calibrated with a digital level to achieve reproducible α with an absolute accuracy better than $\pm 1^\circ$. In the MELBEX III campaign, measurements were taken at $30^\circ \leq \alpha \leq 70^\circ$ with steps of 5° , whereas only $T_B^{p,\alpha}$ measured for $30^\circ \leq \alpha \leq 60^\circ$ were used to explore the vegetation radiative properties based on the foil experiments. At the intermediate angle $\alpha = 45^\circ$ the center of the antenna beam waist is approximately 1.7 m above the base of the ELBARA II scaffold, leading to the height $h = 17$ m, which was used to compute the size (Figure 1b) and the fractional amounts μ^α (Section 2.4) of the footprints for the different α . The latter required knowing the antenna relative sensitivity $D(\Theta)$ with respect to the antenna main direction, for which $D(\Theta = 0^\circ) = 1$. While the system was being constructed, $D(\Theta)$ was derived experimentally by measuring the sun disk moving through the field of view of the antenna (Section 3.2.1 in [28]). For $\Theta \leq 15^\circ$, these data were approximated with the following

Gaussian bell curve (Θ in $^\circ$):

$$D(\Theta) = \exp(-0.01781 \cdot \Theta^2) \quad (2)$$

In agreement with the rotational symmetry of the Pickett-horn [33] antenna in the ELBARA II system, $D(\Theta)$ depends exclusively on the polar angle Θ . This implies that (2) holds for both polarizations received with the two orthogonal $\lambda/4$ -structures implemented in the antenna feed (see Section 2.3 in [28]).

2.4. Foil experiments

The role of the MELBEX III site as the Mediterranean SMOS ground-truth site required dedicated short-term experiments to separate the radiances originating from the vegetation from those emitted by the soil below. To ensure that measured $T_B^{p,\alpha}$ predominantly carried information on vegetation transmissivities $\Gamma^{p,\alpha}$ and optical depths $\tau^{p,\alpha}$, soil emission was shielded by placing a reflecting foil below the vegetation (Figure 1). Hence, approximately 600 m² of metalized foil⁶ was spread out in the trapezoidal shape depicted in Figure 1b to prevent any soil emission from this area.

The dashed ellipses in Figure 1b indicate the projection of the $\pm 9^\circ$ beam angles onto the footprint plane from which the fractional amounts $\mu^\alpha > 0.93$ of the total radiance should originate for $\alpha = 30^\circ, 35^\circ, 40^\circ, 45^\circ, 50^\circ, 55^\circ, 60^\circ$ for a homogeneous footprint. However, due to the trapezoidal shape of the foil, values μ^α for given α and the height $h = 17$ m of the beam waist were computed numerically for this specific setup, taking into consideration the normalized antenna sensitivity $D_N(\Theta^{\alpha,h,\delta})$ derived from (2) and the angle δ representing a possible misalignment of the antenna in azimuth direction:

$$\mu^\alpha = \iint_{\text{foil area}} D_N(\Theta^{\alpha,h,\delta}(x,y)) \cdot d\Omega^{h,\delta}(x,y, dx, dy) \quad (3)$$

⁶ The composite foil is made up of a 12- μm -thick aluminum film inbetween 12 μm of polyester and 75 μm of polyethylene. The thickness of the electrically conductive and paramagnetic aluminum is significantly larger than the skin depth at L band, implying that perfect reflectivity (and hence perfect shielding of the soil emission) can be assumed for the area covered with the foil.

Omitting the algebraic details along with the coordinate transformations and vector geometry, $\Theta^{\alpha,h,\delta}(x,y)$ represents the angle between the antenna main direction at α , h , δ and the view direction of a point in the xy -footprint plane. Seen from the perspective of the radiometer, the solid angle $d\Omega^{h,\delta}(x,y,dx,dy)$ covers an infinitesimal area $dx \cdot dy$, located at a position (x, y) in the footprint plane. The surface integral in (3) was evaluated numerically, yielding the angular dependency of μ^α shown in Figure 2. The error bars indicate results from evaluations performed for $\delta = \pm 3^\circ$, which is large enough to include the possible misalignment of the radiometer in azimuth direction.

All configurations considered in the simulations reveal $\mu^\alpha > 0.93$, with a maximum of $\mu^\alpha = 0.997$ at $\alpha = 35^\circ$. For shallower observations, μ^α decreases and misalignments δ become more relevant, as expected. However, the impact of radiance originating from areas outside the foil-covered part of the footprint on $T_B^{p,\alpha}$ was expected to be very small due to the generally high values μ^α (compare Section 4.1), which implies that uncertainties in the emission of these areas would not significantly affect the retrieved vegetation radiative properties described in Section 5.1.

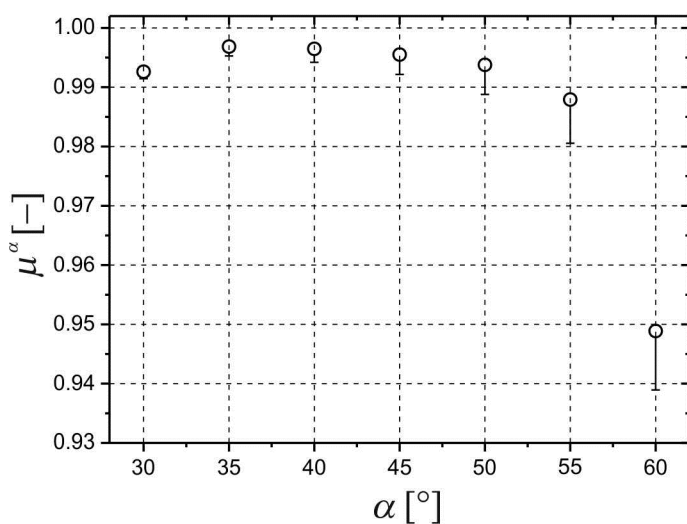


Figure 2: Computed fractional amounts μ^α of radiance originating from the foil-covered (trapezoidal) area (Figure 1b) on a homogeneous footprint at observation angle α . Error bars $\Delta\mu^\alpha$ were computed for a misalignment of the antenna in azimuth direction of $\delta = \pm 3^\circ$.

3. Brightness temperatures

An error analysis of measured $T_B^{p,\alpha}$ to quantify the absolute uncertainties $\Delta T_B^{p,\alpha}$, was important for two reasons: i) to calibrate and validate SMOS data on the basis of ELBARA II measurements; ii) to constrain errors in the vegetation transmissivities $\Gamma^{p,\alpha}$ and optical depth $\tau^{p,\alpha}$ (Section 5) derived from the $T_B^{p,\alpha}$ measured during the foil experiments (see Section 3.2).

3.1. Uncertainties associated with the brightness temperatures measured

As described in Section 2.3, the equations (1) were used to derive $T_B^{p,\alpha}$ from instrumental raw data. To achieve conservative estimates for the corresponding uncertainties $\Delta T_B^{p,\alpha}$ and to take into account the fact that some of the error-prone parameters involved are not correlated with any of the other parameters (e.g. T_{FC}), arithmetic error propagation $\Delta T_B^{p,\alpha} = \sum \Delta X \cdot \left| \partial T_B^{p,\alpha} / \partial X \right|_{\{X\}}$ was applied in conjunction with (1). The summation was performed over the individual parameters involved in (1), and summarized with the symbol $\{X\} \equiv \{T_{RS}, T_{ACS}, U_{RS}, U_{ACS}, U^{p,\alpha}, T_{FC}, t_{fc}\}$, with associated uncertainties $\{\Delta X\} \equiv \{\Delta T_{RS}, \Delta T_{ACS}, \Delta U_{RS}, \Delta U_{ACS}, \Delta U^{p,\alpha}, \Delta T_{FC}\}$. The values of $\{X\}$ and $\{\Delta X\}$ used in the error propagation analysis were derived from the approximately $150 \cdot 10^3$ ELBARA II measurements performed between 19th February 2010 and 1st February 2011 (Section 2). shows the values $\{X\}$ and $\{\Delta X\}$ and summarizes their derivations (these are explained in more detail below).

The statistical uncertainties $\Delta U = \Delta U_{RS}, \Delta U_{ACS}$, and $\Delta U^{p,\alpha}$ of the PDA responses (voltages) $U = U_{RS}, U_{ACS}$, and $U^{p,\alpha}$ were computed from the standard deviations σU of these measurements associated with corresponding noise-power levels $T_{RM\ in} = T_{RS}, T_{ACS}$, and $T_B^{p,\alpha}$, performed with the shortest possible integration time 2.5 ms of ELBARA II. Equation (12) in [28] was used with the system parameters (radiometer gain $G_{RM} = 1.86 \text{ mV K}^{-1}$, radiometer residual noise $T_{RM,0} = 153 \text{ K}$, time-bandwidth product $B\tau = 15868 \text{ Hz s}$, PDA noise $\sigma U_{PDA} = 0.649 \text{ mV}$) determined experimentally during the construction of ELBARA II (Table 2 in [28]). Finally, the three values ΔU used with the arithmetic error propagation were computed as $\Delta U = \sigma U \cdot (f_{LP} \cdot \tau_{rec})^{-1/2}$ with $f_{LP} =$

400 Hz as the cut-off frequency of the PDA, and the integration time $\tau_{\text{rec}} = 3$ s applied to our measurements (corresponding to 1200 independent measurements with 2.5 ms integration time each).

The mean physical temperature T_{FC} of the **Feed Cable (FC)** was approximated with T_{air} measured next to the FC simultaneously with the $T_{\text{B}}^{p,\alpha}$. The assumed uncertainty, $\Delta T_{\text{FC}} = 5$ K, accounts for the temperature variations along the FC connecting the receiver with the antenna ports, which are not of course, taken into account in the simple model (1) used to correct for FC noise. The value of the FC transmission $t_{\text{FC}} = 0.977$ results from its specified loss $L_{\text{FC}} = 0.1$ dB (Section 2.2.1 in [28]). As this value can be considered constant, at least for the period between two sky calibrations, the uncertainty $\Delta t_{\text{FC}} = 0$ is assumed.

Table 1: Values and comments on the parameters $\{X\} \equiv \{T_{\text{RS}}, T_{\text{ACS}}, U_{\text{RS}}, U_{\text{ACS}}, U^{p,\alpha}, T_{\text{FC}}, t_{\text{FC}}\}$ with uncertainties $\{\Delta X\} \equiv \{\Delta T_{\text{RS}}, \Delta T_{\text{ACS}}, \Delta U_{\text{RS}}, \Delta U_{\text{ACS}}, \Delta U^{p,\alpha}, \Delta T_{\text{FC}}\}$ used to compute $\Delta T_{\text{B}}^{p,\alpha}$ shown in Figure 3

$\{X\}$	$\{\Delta X\}$	Comments
$T_{\text{RS}} = 313$ K	$\Delta T_{\text{RS}} = 71$ mK $\sigma T_{\text{RS}} = 71$ mK	Mean internal physical temperature, measured with associated standard deviation (Section 2.3a)
$U_{\text{RS}} = 1.11$ V	$\Delta U_{\text{RS}} = 199$ μ V $\sigma U_{\text{RS}} = 199$ μ V	Mean PDA response (voltage) for the RS with associated statistical uncertainty σU_{RS} (Section 2.3a)
$T_{\text{ACS}} = 37.8$ K	$\Delta T_{\text{ACS}} = 631$ mK $\sigma T_{\text{ACS}} = 631$ mK	Mean ACS temperature, derived from sky calibrations with associated standard deviation (Section 2.3a)
$U_{\text{ACS}} = 0.471$ V	$\Delta U_{\text{ACS}} = 83$ μ V $\sigma U_{\text{ACS}} = 83$ μ V	Mean PDA response (voltage) for the ACS with associated standard deviation σU_{ACS} (Section 2.3a)
$U^{p,\alpha} = 0.75$ V – 1.21 V	$\Delta U^{p,\alpha} = \sigma U^{p,\alpha}$	Mean PDA response (voltage) for antenna measurements with associated statistical uncertainty $\sigma U^{p,\alpha}$ (Section 2.3a)
$T_{\text{FC}} = 14.5$ °C	$\Delta T_{\text{FC}} = 5$ K	Mean T_{air} measured with estimated temperature difference at along the FC
$t_{\text{FC}} = 0.977$	$\Delta t_{\text{FC}} = 0$	Specified FC transmissivity

The absolute uncertainties $\Delta T_{\text{B}}^{p,\alpha}$ computed with arithmetic error propagation applied to (1) also depend on the values of $T_{\text{B}}^{p,\alpha}$ measured. Hence, $\Delta T_{\text{B}}^{p,\alpha}$ (Figure 3) are estimated for the

range $0 \text{ K} \leq T_B^{p,\alpha} \leq 370 \text{ K}$ to represent all the situations at horizontal and vertical polarization observed during the foil experiments, as well as during the measurements performed on the undisturbed vineyard. Considering the corresponding ranges of $T_B^{p,\alpha}$ (large arrows in Figure 3), the range of uncertainty expected for $T_B^{p,\alpha}$ measured with the reflecting foil below the vine vegetation was $0.69 \text{ K} < \Delta T_B^{p,\alpha} < 0.94 \text{ K}$, and $0.57 \text{ K} < \Delta T_B^{p,\alpha} < 0.74 \text{ K}$ for the measurements on the undisturbed vineyard.

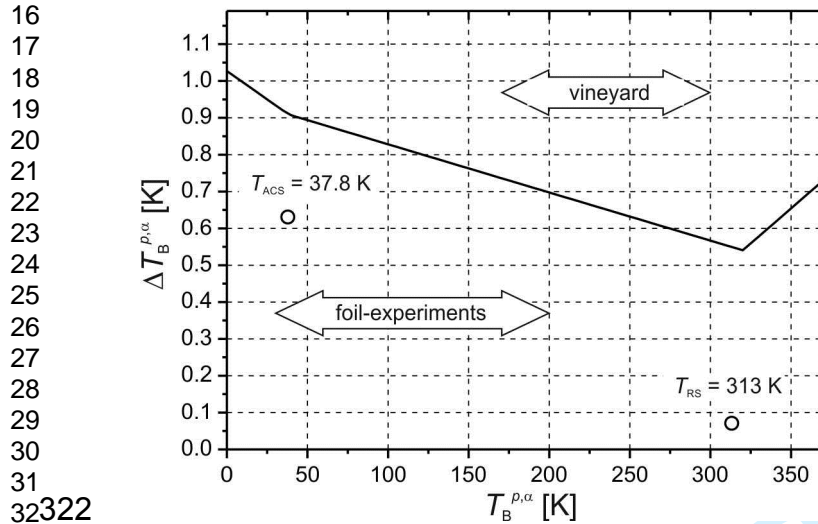


Figure 3: Uncertainties $\Delta T_B^{p,\alpha}$ of $T_B^{p,\alpha}$ measured with ELBARA II. The noise temperatures, T_{ASC} and T_{RS} , of internal reference sources, and ranges of $T_B^{p,\alpha}$ measured during the foil experiments and on the undisturbed vineyard are indicated.

3.2. Brightness temperatures measured during the foil experiments

Since ELBARA II was commissioned in September 2009, it has provided calibrated $T_B^{p,\alpha}$ for $p = H, V$ and $30^\circ \leq \alpha \leq 70^\circ$ that are currently being analyzed within the framework of the ongoing SMOS calibration and validation activities. While the reflecting foil has been laid out, sequences of $T_B^{p,\alpha}$ were measured for $30^\circ \leq \alpha \leq 60^\circ$ to derive transmissivities $\Gamma^{p,\alpha}$ and optical depths $\tau^{p,\alpha}$ with different vegetation states (Section 5). Comparable measurements of $T_B^{p,\alpha}$ at the vineyard with similar vegetation states and without any foil below the vines were used to comprise the combined emissions of vegetation and soil (Section 4.1, equation (7)). Figure 4 shows the data sequences T_{ws_f} , T_{ws_nf} and T_{ss_f} , T_{ss_nf} , where “ws” refers to the winter state of the

vineyard and “ss” indicates the summer state. The index “f” indicates the periods when the foil was under the vines and “nf” refers to the periods when no foil was under the vines with the same developmental states. The bottom rows in Figure 4 show air temperatures T_{air} measured next to the radiometer at the same time as the $T_B^{p,\alpha}$.

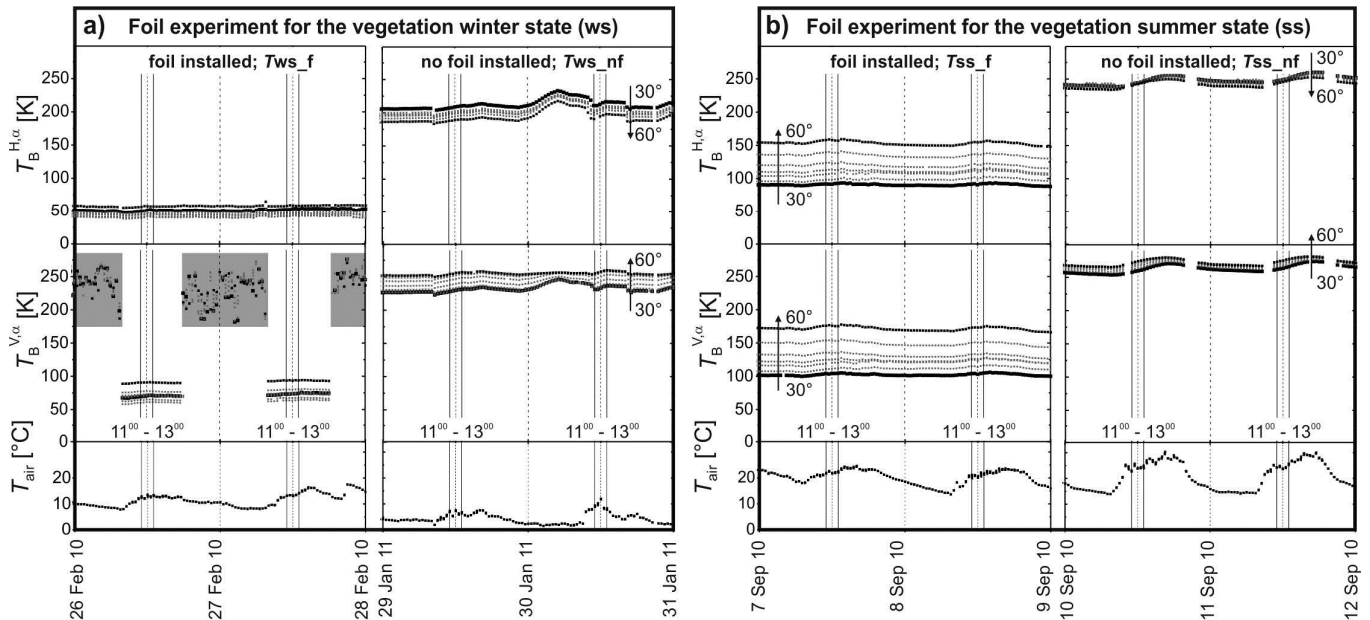


Figure 4: Time series of $T_B^{p,\alpha}$ measured for $p = H, V$ and $\alpha = 30^\circ$ (bold black), $35^\circ, 40^\circ, 45^\circ, 50^\circ, 55^\circ$ (gray), 60° (black). Arrows indicate trends of angular dependencies of $T_B^{p,\alpha}$. Gray shaded boxes indicate RFI distorted $T_B^{V,\alpha}$. The data used to derive the radiative properties of the vegetation's winter state and its fully developed state are constrained to time periods between 11^{00} and 13^{00} indicated in a) and b), respectively. $T_B^{p,\alpha}$ measured with the foil on the soil are shown in the left columns of a) and b). The right columns show $T_B^{p,\alpha}$ of the vineyard without the foil below the vines with the same vegetation states. The bottom rows show T_{air} measured on the tower at the same time as $T_B^{p,\alpha}$.

During the period T_{ws_f} , distinct RFI was observed exclusively at V-polarization every day between 19^{00} and 7^{30} (indicated by the gray shaded boxes). The data from the four two-day periods T_{ws_f} (26. – 27. February 2010), T_{ws_nf} (29. – 30. January 2011) and T_{ss_f} (7. – 8. September 2010), T_{ss_nf} (10. – 11. September 2010) were further constrained to the hours 11^{00} – 13^{00} for analysis because this measure improves the comparability between $\Gamma^{p,\alpha}$ and $\tau^{p,\alpha}$ retrieved for different vegetation states. Moreover, the RFI-distorted periods had to be excluded from the analysis.

The $T_B^{p,\alpha}$ shown in Figure 4 differ significantly for all time periods T_{ws_f} , T_{ws_nf} and T_{ss_f} , T_{ss_nf} . Qualitatively, the angular dependence of the $T_B^{p,\alpha}$ measured for the winter state of the vineyard with no foil (T_{ws_nf}) corresponds to the emission expected for a specular (Fresnel)

1 348 surface ($T_B^{V,\alpha} > T_B^{H,\alpha}$ and decreasing $T_B^{H,\alpha}$ with increasing α , while $T_B^{V,\alpha}$ increases with α). In
 2
 3 349 contrast, the sensitivity of $T_B^{p,\alpha}$ with respect to α is generally less pronounced during the
 4
 5
 6 350 undisturbed vegetation summer state (T_{ss_nf}) and some of the $T_B^{p,\alpha}$ even respond in the
 7
 8
 9 351 opposite way. The $T_B^{p,\alpha}$ measured for the vegetation winter state with the foil (T_{ws_f}) were rather
 10
 11 352 small ($35\text{ K} < T_B^{p,\alpha} < 100\text{ K}$) and no clear trend with α can be identified. Again, with the summer
 12
 13
 14 353 vegetation state and the foil (T_{ss_f}), the behavior was significantly different. Here the $T_B^{p,\alpha}$
 15
 16 354 increased with α at both polarizations, and the sensitivity with respect to α distinctly increased in
 17
 18
 19 355 comparison with the period T_{ws_f} during the vegetation winter state with the foil. In summary, the
 20
 21 356 state of the vegetation became primarily apparent in the angular dependencies of the $T_B^{p,\alpha}$
 22
 23 357 measured, as well as in the overall magnitudes.

27 358 4. Modeling approach

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 29
 30 359 The following sub-sections describe the models used to quantify transmissivities $\Gamma^{p,\alpha}$ and
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 32 360 optical depths $\tau^{p,\alpha}$ of the vegetation at different developmental stages for H- and V- polarization
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 34
 35 361 on the basis of the $T_B^{p,\alpha}$ and T_{air} shown in Figure 4.

38 362 4.1. Microwave radiative transfer

41 363 The thermal L-band emissions $T_B^{p,\alpha}$ of the vineyards during the periods with no foil (periods
 42
 43 364 T_{ws_nf} and T_{ss_nf} in Figure 4) are modeled with the very simple radiative transfer approach (4).
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 45
 46 365 It uses the merged reflectivity $R_{vine}^{p,\alpha}$ of the vine vegetation and soil and the effective
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 48
 49 366 temperature T_{vine} of the vineyard, and assumes that the temperature is the same all over the site:

$$51 367 T_B^{p,\alpha} = (1 - R_{vine}^{p,\alpha}) T_{vine} + R_{vine}^{p,\alpha} T_{sky} \quad (4)$$

53
 54
 55 368 Modeling $T_B^{p,\alpha}$ of areas with the highly reflective foil underneath the vines requires a more
 56
 57 369 sophisticated approach. With increasing ground reflection, multiple reflections across the
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 59
 60 370 vegetation become increasingly relevant, and the zero-order scattering model [34], also called
 371 the $\tau - \omega$ model [9, 35, 36], is therefore not an appropriate choice. To account for multiple

reflections, we use the multiple-scattering approach (5) described in [37, Section 4.2.5.1] to model $T_B^{p,\alpha}$ emitted from areas with the reflecting foil. In (5), T_G and T_V are the effective temperatures of the ground and the vegetation, and $R_G^{p,\alpha}$ is the ground reflectivity:

$$T_B^{p,\alpha} = T_G a_G + T_V a_V + T_{\text{sky}} (1 - a_G - a_V) \quad \text{with} \quad (5)$$

$$a_G = t_V \frac{1 - R_G^{p,\alpha}}{1 - R_G^{p,\alpha} r_V}$$

$$a_V = (1 - r_V - t_V) \frac{1 + R_G^{p,\alpha} (t_V - r_V)}{1 - R_G^{p,\alpha} r_V}$$

The equations (4.13) and (4.14) in [37] define the reflectivity r_V and the transmissivity t_V of the scattering vegetation layer. For moderate scattering, these can be approximated with:

$$r_V = r_\infty (1 - \Gamma^{p,\alpha 2}) \quad \text{and} \quad t_V = \Gamma^{p,\alpha} (1 - r_\infty^2) \quad \text{with} \quad r_\infty \cong \frac{\omega^{p,\alpha}}{2} \quad (6)$$

Where the reflectivity r_∞ of the vegetation at infinite thickness is given by equation (4.16) in [37]. Considering that scattering in the backward hemisphere is much smaller than absorption, (4.17) [37] can be approximated with a corresponding first-order Taylor expansion. Using this approximation in (4.16) and considering the definitions (4.2) relates r_∞ to the effective scattering albedo $\omega^{p,\alpha}$, as it is expressed by the third relation in (6).

The denominators $(1 - R_G^{p,\alpha} \cdot r_V)$ in (5) express the infinite reflections within the vegetation layer, which obviously become dominant if the ground is perfectly reflecting ($R_G^{p,\alpha} = 1$) because of the metalized foil. Furthermore, it can easily be shown that this multiple-scattering emission model becomes equivalent to the zero-order $\tau - \omega$ model for $\omega^{p,\alpha} = 0$, which then represents non-scattering vegetation. Although the assumption $\omega^{p,\alpha} = 0$ is often made for low growing vegetation types, this is not necessarily adequate for vineyards since grapevines have a significant amount of woody matter with dimensions comparable with the L-band wavelengths (≈ 21 cm). This is why we considered the range $0 \leq \omega^{p,\alpha} \leq 0.1$ in the analysis presented in Section 5.

The sky radiance T_{sky} used in (4) and (5) was computed with [30] for the elevation 750 m a.s.l. of the MELBEX III site, the T_{air} measured, and the direction of the downwelling T_{sky} received by

1 394 the radiometer after its forward reflection at the ground. For $-3\text{ }^{\circ}\text{C} < T_{\text{air}} < 40\text{ }^{\circ}\text{C}$ and
 2
 3 395 $30^{\circ} \leq \alpha \leq 60^{\circ}$, the associated sky brightness temperatures are in the range of $4.45\text{ K} \leq T_{\text{sky}} \leq$
 4
 5
 6 396 5.54 K . Furthermore, T_{air} measured was used for all the effective temperatures involved in (4)
 7
 8 397 and (5), and the resulting errors are analyzed.

10
 11 398 During the periods $T_{\text{ws_f}}$ and $T_{\text{ss_f}}$, the $T_{\text{B}}^{p,\alpha}$ measured comprise contributions of radiances
 12
 13 399 $T_{\text{B,f}}^{p,\alpha}$ and $T_{\text{B,vine}}^{p,\alpha}$ originating from the area with the reflecting foil, and from the adjacent
 14
 15
 16 400 undisturbed vineyard, respectively. The radiances, $T_{\text{B,f}}^{p,\alpha}$ and $T_{\text{B,vine}}^{p,\alpha}$, emitted from within the
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 18 401 antenna's field of view were weighted with the fractional amounts μ^{α} and $(1 - \mu^{\alpha})$, respectively,
 19
 20
 21 402 shown in Figure 2:

$$24 403 \quad T_{\text{B}}^{p,\alpha} = \mu^{\alpha} T_{\text{B,f}}^{p,\alpha} + (1 - \mu^{\alpha}) T_{\text{B,vine}}^{p,\alpha} \quad (7)$$

26
 27 404 Where, (4) is used to represent $T_{\text{B,vine}}^{p,\alpha}$, and (5) and (6) is used to express $T_{\text{B,f}}^{p,\alpha}$ with $R_{\text{G}}^{p,\alpha} = 1$
 28
 29
 30 405 to represent the perfect reflection of the metallized foil.

33 406 **4.2. Vegetation transmissivities and uncertainties**

34
 35
 36 407 Vegetation transmissivities $\Gamma^{p,\alpha}$ were derived for the vegetation winter state (ws) and the
 37
 38 408 summer state (ss) from the $T_{\text{B}}^{p,\alpha}$ shown in Figure 4. The weighting approach (7), with the
 39
 40
 41 409 radiative transfer models (4), (5), and (6) is solved numerically for $\Gamma^{p,\alpha}$ with inserted $T_{\text{B}}^{p,\alpha}$
 42
 43 410 measured during the periods $T_{\text{ws_f}}$ and $T_{\text{ss_f}}$. The effective physical temperatures, T_{vine} of the
 44
 45
 46 411 vineyard and T_{V} of the vegetation were both approximated with air temperatures T_{air} measured at
 47
 48 412 the radiometer. Of course, the assumption, $T_{\text{vine}} = T_{\text{V}} = T_{\text{air}}$ introduces certain errors that are
 49
 50 413 estimated as $\Delta T_{\text{vine}} = \Delta T_{\text{V}} = 5\text{ K}$ to represent upper limits. The uncertainties $\{\Delta Y\} \equiv \{\Delta \mu^{\alpha}, \Delta T_{\text{B}}^{p,\alpha},$
 51
 52
 53 414 $\Delta T_{\text{V}}, \Delta T_{\text{vine}}, \Delta R_{\text{vine}}^{p,\alpha}, \Delta T_{\text{sky}}, \Delta \omega^{p,\alpha}\}$ of the parameters $\{Y\} \equiv \{\mu^{\alpha}, T_{\text{B}}^{p,\alpha}, T_{\text{V}}, T_{\text{vine}}, R_{\text{vine}}^{p,\alpha}, T_{\text{sky}}, \omega^{p,\alpha}\}$
 54
 55 415 involved in (7) (with (4), (5), and (6) substituted) were used with arithmetic error propagation to
 56
 57
 58 416 achieve conservative estimates of absolute uncertainties $\Delta \Gamma^{p,\alpha} = \sum \Delta Y \cdot \left| \partial \Gamma^{p,\alpha} / \partial Y \right|_{\{Y\}}$ of the
 59
 60
 417 transmissivities $\Gamma^{p,\alpha}$ (summation was performed over the parameters).

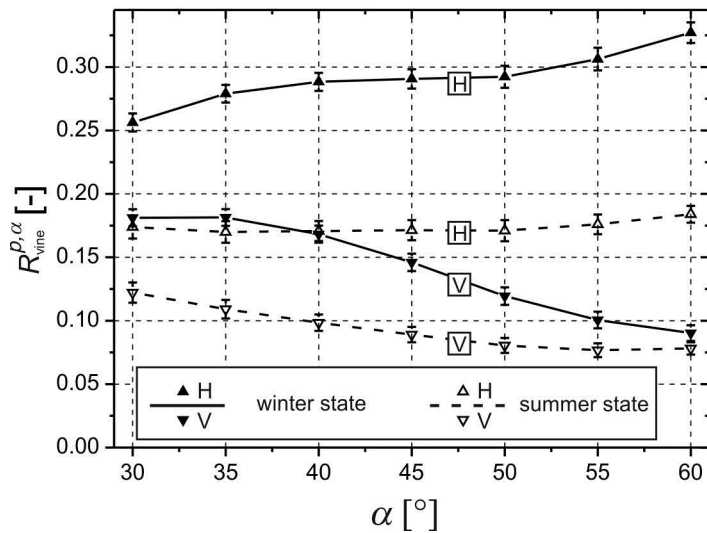


Figure 5: Mean values of reflectivities $R_{vine}^{p,\alpha}$ of the vineyard for the winter and summer states derived from measurements performed during the periods T_{ws_nf} and T_{ss_nf} (Figure 4).

The reflectivities of the vineyard outside the foil-covered area used in (4) were estimated as the mean values $R_{vine}^{p,\alpha}$ derived from the time-series of vineyard reflectivities deduced from measurements during the time periods T_{ws_nf} and T_{ss_nf} shown in the right columns in Figure 4 a) and b). The resulting $R_{vine}^{p,\alpha}$ for the winter- (solid symbols) and the summer state (empty symbols) at H-(up triangles) and V-polarization (down triangles) are depicted in . The angular dependency of $R_{vine}^{p,\alpha}$ observed for the winter state behaved similarly to what could be expected for a Fresnelian reflector, i.e. increasing $R_{vine}^{H,\alpha}$ with increasing α , and $R_{vine}^{V,\alpha}$ reaches a minimum when α approaches the Brewster angle. The $R_{vine}^{p,\alpha}$ of the vineyard during summer is clearly less sensitive to α , which is rather typical for a diffuse reflector. Hence, the $R_{vine}^{p,\alpha}$ demonstrate the marked effect of the vegetation state on the angular dependency of the L-band signatures even more distinctly than the measured $T_B^{p,\alpha}$ presented in Section 3.2. The error bars in represent standard deviations $\sigma R_{vine}^{p,\alpha}$ deduced for the time series of the vineyard reflectivities measured for the periods T_{ws_nf} and T_{ss_nf} (right columns in Figure 4 a) and b)), and were used to estimate the uncertainties $\Delta R_{vine}^{p,\alpha}$ of $R_{vine}^{p,\alpha}$.

As an upper limit for the uncertainty of the model-based sky radiance T_{sky} , we assumed $\Delta T_{sky} = 1$ K. For μ^α , the values shown in Figure 2 were used together with the uncertainties $\Delta \mu^\alpha$

1 437 computed for a misalignment $\delta = \pm 3^\circ$ between the radiometer plane of incidence and the
 2
 3 438 symmetry axes of the trapezoidal foil. The uncertainties $\Delta T_B^{p,\alpha}$ of the measured $T_B^{p,\alpha}$ used to
 4
 5
 6 439 derive $\Gamma^{p,\alpha}$ were taken into account by the relation $\Delta T_B^{p,\alpha}(T_B^{p,\alpha})$ shown in Figure 3. The sensitivity
 7
 8
 9 440 of the $\Gamma^{p,\alpha}$ to the effective single-scattering albedo $\omega^{p,\alpha}$ was analyzed by considering the two
 10
 11 441 values $\omega^{p,\alpha} = 0$ and $\omega^{p,\alpha} = 0.1$, which are believed to include the existing range of uncertainty.
 12
 13
 14 442 Brief comments on the origin of the parameters values $\{Y\}$ and the associated uncertainties $\{\Delta Y\}$
 15
 16 443 are given in Table 2.

18 444

20
 21 **Table 2:** Values and comments on the parameters
 22 $\{Y\} \equiv \{\mu^\alpha, T_B^{p,\alpha}, T_V, T_{vine}, R_{vine}^{p,\alpha}, T_{sky}, \omega^{p,\alpha}\}$
 23 with uncertainties $\{\Delta Y\} \equiv \{\Delta\mu^\alpha, \Delta T_B^{p,\alpha}, \Delta T_V,$
 24 $\Delta T_{vine}, \Delta R_{vine}^{p,\alpha}, \Delta T_{sky}, \Delta\omega^{p,\alpha}\}$ used to derive
 25 $\Gamma^{p,\alpha}$ and $\Delta\Gamma^{p,\alpha}$.

$\{Y\}$	$\{\Delta Y\}$	Comments
μ^α	$\Delta\mu^\alpha$	Computed values shown in Figure 2
$T_B^{p,\alpha}$	$\Delta T_B^{p,\alpha}$	Measured values (Figure 4) with uncertainties computed (Figure 3)
$T_V = T_{air}$	$\Delta T_V = 5 \text{ K}$	Measured values (Figure 4) with assumed uncertainty
$T_{vine} = T_{air}$	$\Delta T_{vine} = 5 \text{ K}$	Measured values (Figure 4) with assumed uncertainty
$R_{vine}^{p,\alpha}$	$\Delta R_{vine}^{p,\alpha} = \sigma R_{vine}^{p,\alpha}$	Values measured during Tss_nf and Tws_nf () with standard deviations indicated
T_{sky}	$\Delta T_{sky} = 1 \text{ K}$	Computed with [30] and uncertainty assumed
$\omega^{p,\alpha} = 0$ and 0.1	$\Delta\omega^{p,\alpha} = 0$	Feasible range for the MELBEX III vineyard

45 445 46 **4.3. Vegetation optical depth**

47
 48 446 Vegetation optical depths $\tau^{p,\alpha}$ along the view in the direction of the observation angle α and
 49
 50 447 the optical depths $\tau_0^{p,\alpha}$ in the nadir direction, can be deduced from the corresponding
 51
 52
 53 448 transmissivities $\Gamma^{p,\alpha}$ using Beer's law if isotropy of vegetation absorption can be assumed:

$$54$$

$$55$$

$$56 449 \tau^{p,\alpha} = -\ln(\Gamma^{p,\alpha}) \quad \tau_0^{p,\alpha} = \tau^{p,\alpha} \cdot \cos \alpha \quad (8)$$

$$57$$

$$58$$

$$59$$

$$60$$

1 450 However, we have to take into account the fact that vegetation often shows bi-axial anisotropy
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 3 451 [10, 13, 14, 38]⁷. In the L-MEB model [27], vegetation anisotropy is accounted for by using the
 4
 5 452 following empirical approach:
 6

$$9 \ 453 \quad \tau_0^p(\alpha) = \tau_{\text{NAD}} \left[tt^p \cdot \sin^2 \alpha + \cos^2 \alpha \right] \quad (9)$$

10
 11
 12 454 The parameters τ_{NAD} and tt^p ($p = \text{H}, \text{V}$) were determined simultaneously in L-MEB retrievals by
 13
 14 455 applying an optimization approach to multi-angular $T_{\text{B}}^{p,\alpha}$ -data measured, e.g., with SMOS. In
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 16
 17 456 Section 5.2, τ_{NAD} and tt^p are quantified according to ground-based measurements that can be
 18
 19 457 compared with the corresponding L-MEB retrievals from SMOS measurements over the VAS
 20
 21
 22 458 site. These “ground truth” values of the parameters τ_{NAD} , tt^{H} , tt^{V} involved in $\tau_0^p(\alpha)$ given by (9) are
 23
 24 459 determined by minimizing the objective function OF (summation is over the observation angles α
 25
 26
 27 460 measured):
 28

$$30 \ 461 \quad OF = \sum_{\alpha} \left[\left(\tau_0^{\text{H}}(\alpha) - \tau_0^{\text{H},\alpha} \right)^2 + \left(\tau_0^{\text{V}}(\alpha) - \tau_0^{\text{V},\alpha} \right)^2 \right] \quad (10)$$

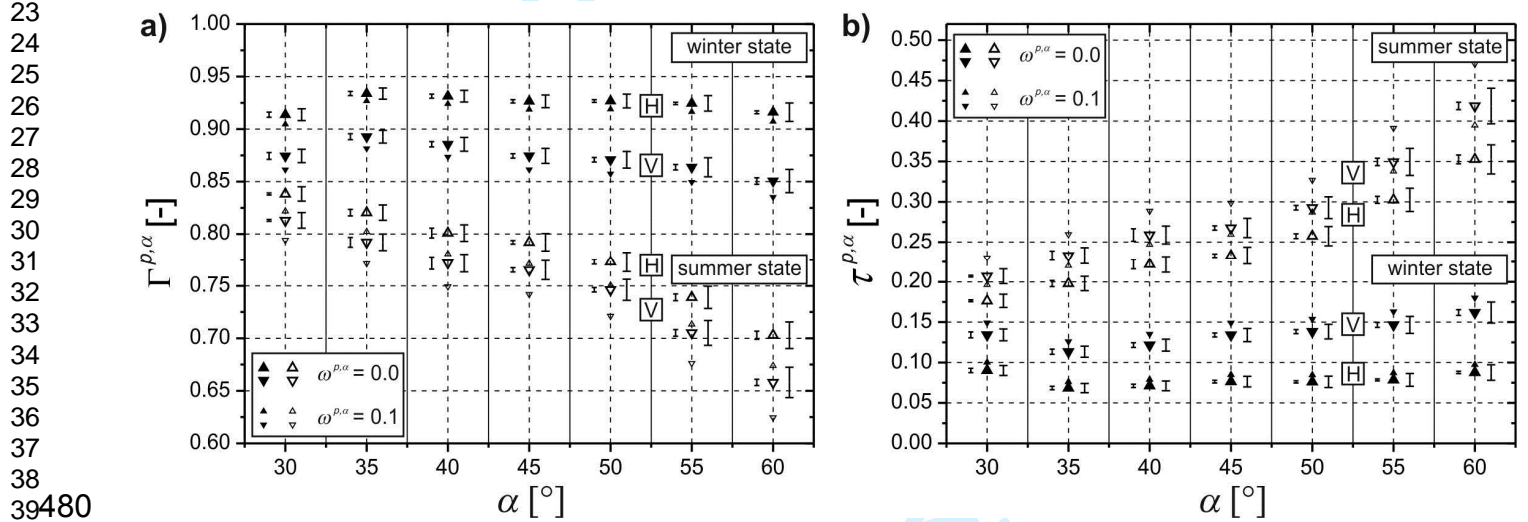
35 462 5. Results and Discussion

38 463 5.1. Vegetation transmissivities and optical depth

41 464 Transmissivities $\Gamma^{p,\alpha}$ and uncertainties $\Delta\Gamma^{p,\alpha}$ of the vineyard vegetation in the winter state and
 42
 43 465 the fully developed summer state were derived from $T_{\text{B}}^{p,\alpha}$ and T_{air} measured during the two-hour
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 45 466 periods (11⁰⁰ - 13⁰⁰) indicated in Figure 4. The radiative transfer approaches given in Section 4
 46
 47 467 solved for $\Gamma^{p,\alpha}$ were used with the parameter values $\{Y\}$ and $\{\Delta Y\}$ explained in Table 2. The
 48
 49 468 resulting $\Gamma^{p,\alpha}$ for $30^\circ \leq \alpha \leq 60^\circ$, at horizontal ($p = \text{H}$, up triangles) and vertical ($p = \text{V}$, down
 50
 51 469 triangles) polarization are depicted in Figure 6a for the assumptions $\omega^{p,\alpha} = 0$ (large symbols) and
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 53 470 $\omega^{p,\alpha} = 0.1$ (small symbols). The error bars to the right of the large symbols (large caps) are the
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 55
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 57
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⁷ Predominant orientation of vegetation components (branches, stems, leaves) can lead to different propagation of horizontal and vertical field modes.

1 471 mean uncertainties $\Delta\Gamma^{p,\alpha}$ of single $\Gamma^{p,\alpha}$ (for $\omega^{p,\alpha} = 0$) estimated from the uncertainties $\{\Delta Y\}$ using
 2
 3 472 arithmetic error propagation (Section 4.2). The error bars to the left (smaller caps) of the large
 4
 5
 6 473 symbols represent the standard deviations $\sigma\Gamma^{p,\alpha}$ of the single $\Gamma^{p,\alpha}$ (for $\omega^{p,\alpha} = 0$) derived from $T_B^{p,\alpha}$
 7
 8 474 and T_{air} measured for a given α . Panel b of Figure 6 shows optical depth $\tau^{p,\alpha}$ (again for the
 9
 10
 11 475 assumptions $\omega^{p,\alpha} = 0$ and $\omega^{p,\alpha} = 0.1$) diagonally through the vegetation computed from $\Gamma^{p,\alpha}$ using
 12
 13 476 (8). The error bars to the right of the large symbols (large caps) are the mean uncertainties
 14
 15
 16 477 $\Delta\tau^{p,\alpha} = \Delta\Gamma^{p,\alpha} / \Gamma^{p,\alpha}$ of the single $\tau^{p,\alpha}$ (for $\omega^{p,\alpha} = 0$), while the error bars to the left of the large
 17
 18 478 symbols (smaller caps) are standard deviations $\sigma\tau^{p,\alpha}$ of the $\tau^{p,\alpha}$ (for $\omega^{p,\alpha} = 0$) derived for specific
 19
 20
 21 479 α .



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 40
 41 **Figure 6:** **a)** Transmissivities $\Gamma^{p,\alpha}$ at horizontal (up triangles) and vertical (down triangles) polarization as
 42 functions of the observation angle α retrieved for the winter state and the summer state of the
 43 vegetation as functions of the observation angle α , and for horizontal (up triangles) and vertical (down
 44 triangles) polarization. $\Gamma^{p,\alpha}$ are derived assuming $\omega^{p,\alpha} = 0$ (large symbols) and $\omega^{p,\alpha} = 0.1$ (small
 45 symbols). The error bars to the right of the large symbols (large caps) are the mean uncertainties $\Delta\Gamma^{p,\alpha}$
 46 of single $\Gamma^{p,\alpha}$. The error bars to the left of the large symbols (smaller caps) are the standard deviations
 47 $\sigma\Gamma^{p,\alpha}$ of the $\Gamma^{p,\alpha}$ measured for a given α . **b)** Vegetation optical depth $\tau^{p,\alpha}$ diagonally through the
 48 vegetation with errors bars corresponding to those in panel a).

50 481 The angular dependency of the transmissivity $\Gamma^{p,\alpha}$ of the vegetation in the summer state
 51
 52 (empty triangles) shows a clear decreasing trend with increasing α at H- and V-polarization. In
 53 482 the winter state, $\Gamma^{p,\alpha}$ is generally larger than in the summer state, and the angular dependence is
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 55 483 less pronounced with a small decreasing trend for increasing α with $\alpha \geq 35^\circ$. Furthermore, $\Gamma^{H,\alpha}$ is
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 57
 58 484 persistently larger than $\Gamma^{V,\alpha}$ for both vegetation states. The standard deviations $\sigma\Gamma^{p,\alpha}$ (error bars
 59
 60 485 to the left of the large symbols) of the ≈ 160 samples $\Gamma^{p,\alpha}$ considered are smaller than the mean
 486 page 23 of 31

1 487 uncertainties $\Delta\Gamma^{p,\alpha}$ (error bars to the right of the large symbols) estimated for the individual $\Gamma^{p,\alpha}$
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 3 488 with $\omega^{p,\alpha} = 0$. This indicates that the assumptions made for the parameter uncertainties $\{\Delta Y\}$
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 6 489 used to compute $\Delta\Gamma^{p,\alpha}$ by arithmetic error propagation (Section 4.2) are conservative enough to
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 9 490 interpret $\Delta\Gamma^{p,\alpha}$ as upper boundaries of the uncertainties. To address concerns about the
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 11 491 somewhat critical assumption $\omega^{p,\alpha} = 0$ made in L-MEB retrievals applied to vineyards at VAS, the
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 13 492 sensitivity of the $\Gamma^{p,\alpha}$ shown in Figure 6a with respect to the single scattering albedo $\omega^{p,\alpha}$ was
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 16 493 analyzed. To this end, $\Gamma^{p,\alpha}$ were derived from the multiple-scattering emission model described in
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 19 494 Section 4 assuming $\omega^{p,\alpha} = 0.1$ (small triangles in Figure 6a), which is possible with specific types
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 21 495 of low growing vegetation [38]. This accounts for vegetation volume scattering and results in an
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 23 496 overall decrease in the estimated $\Gamma^{p,\alpha}$ (small symbols) in comparison with the $\Gamma^{p,\alpha}$ (large symbols)
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 26 497 derived for the non-scattering vegetation ($\omega^{p,\alpha} = 0.0$). Of course, all of the findings also apply to
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 28 498 optical depth $\tau^{p,\alpha}$ shown in Figure 6b) if the definition (8) relating $\Gamma^{p,\alpha}$ to $\tau^{p,\alpha}$ is considered.
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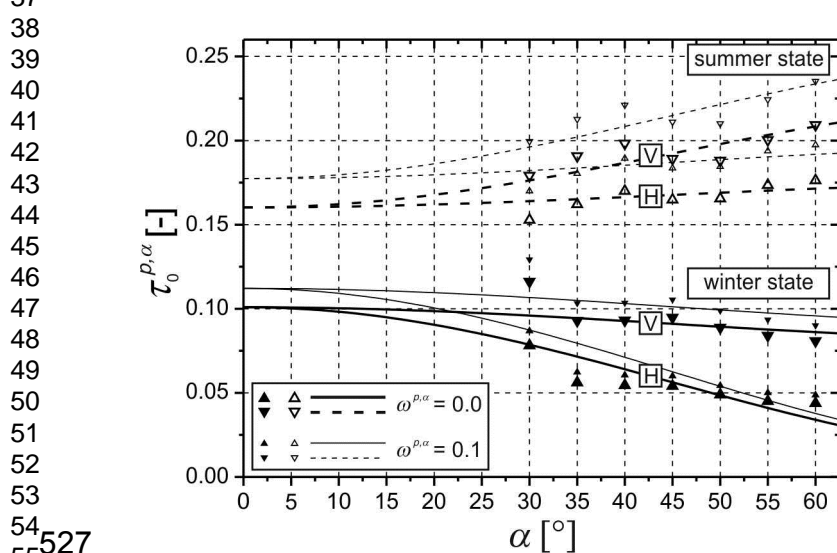
32 499 **5.2. Comparison of vegetation parameters**

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 35 500 As outlined in Section 4.3 the effects of vegetation anisotropy on the angular and polarization
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 37 501 dependence of $\tau^{p,\alpha}$ were considered in the L-MEB retrievals by using (8) and the empirical
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 40 502 approach (9) comprising the parameters τ_{NAD} and tt^{H} , tt^{V} . These values were quantified on the
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 42 503 basis of the $\tau^{p,\alpha}$, shown in Figure 6b, by first applying (8) to correct the $\tau^{p,\alpha}$ for the elongation of
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 45 504 the path through the vegetation layer. The resulting $\tau_0^{p,\alpha}$, shown in Figure 7 (the symbols are
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 47 505 explained in Figure 6), were then used to minimize the objective function (10), yielding the values
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 50 506 τ_{NAD} , and tt^{H} , tt^{V} . These values can be considered as “ground-truth”, and are therefore valuable
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 52 507 for the SMOS calibration and validation activities taking place at the VAS site.
 53

54 508 The $\tau_0^{p,\alpha}$ shown in Figure 7 reveal a decent decreasing trend with increasing α for the
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 56
 57 509 vegetation winter state. In contrast, a slightly increasing trend of $\tau_0^{p,\alpha}$ is evident for the summer
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 59 510 state. This is qualitatively different from the angular dependency of $\tau^{p,\alpha}$ (Figure 6b), which still
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 511 includes the effect of the increasing path length through the vegetation with increasing α . The

1 512 opposite angular trends of $\tau_0^{p,\alpha}$ observed for the two vegetation states indicate changing
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 3 513 vegetation anisotropies in the course of vegetation development.

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 6 514 The bold solid and dashed lines in Figure 7 represent the empirical model $\tau_0^p(\alpha)$ given by (9),
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 8 515 fitted to the $\tau_0^{p,\alpha}$ for the non-scattering vegetation ($\omega^{p,\alpha} = 0.0$). The corresponding fine lines show
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 11 516 $\tau_0^p(\alpha)$ fitted to $\tau_0^{p,\alpha}$ for $\omega^{p,\alpha} = 0.1$. The best-fit values of the parameters τ_{NAD} , tt^H , tt^V to represent
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 13 517 the angular dependency of $\tau_0^{p,\alpha}$ for the vegetation states considered with $\omega^{p,\alpha} = 0.0$ and $\omega^{p,\alpha} =$
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 16 518 0.1, respectively, are shown in Table 3. As can be seen, τ_0 retrieved for $\omega^{p,\alpha} = 0.0$ and 0.1 of the
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 18 519 vegetation in its fully developed summer state is increased by approximately 60% compared with
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 21 520 τ_0 of the vegetation in the winter state. As a consequence of the still observable angular
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 23 521 dependence of $\tau_0^{p,\alpha}$ (Figure 7), the values tt^p deviate from zero. Values $tt^p < 1$ represent
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 26 522 increasing $\tau_0^{p,\alpha}$ with increasing α in accordance with the trend observed for the vegetation winter
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 28 523 state. The values $tt^p > 1$ represent the opposite trend of $\tau_0^{p,\alpha}$, observed for the fully developed
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 30
 31 524 summer state of the vegetation. Furthermore, τ_{NAD} retrieved with the assumption $\omega^{p,\alpha} = 0.1$ are
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 33 525 slightly increased compared with τ_{NAD} retrieved without considering volume scattering ($\omega^{p,\alpha} =$
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 36 526 0.0).



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Figure 7: Optical depths $\tau_0^{p,\alpha}$ derived from $\tau^{p,\alpha}$ shown in Figure 6b using (8). The symbols are in correspondance with those in Figure 6. The lines represent $\tau_0^p(\alpha)$ given by (9) with the best-fit values for τ_{NAD} , tt^H , tt^V shown in Table 3.

Table 3: Values of best fit-parameters τ_{NAD} , tt^{H} , tt^{V} derived with (10) to reproduce the $\tau_0^{p,\alpha}$ shown in Figure 7.

Vegetation state:	$\omega^{p,\alpha}$	τ_{NAD}	tt^{H}	tt^{V}
Winter	0.0	0.101	0.116	0.804
Summer	0.0	0.160	1.093	1.401
Winter	0.1	0.112	0.116	0.805
Summer	0.1	0.177	1.108	1.423

The retrieved “ground-truth” values of τ_{NAD} (Table 3) obtained for the MELBEX III vineyard agree well with preliminary L-MEB retrievals applied to SMOS observation over the VAS area. During the winter state, the effective optical depth of the vine stocks $\tau_{\text{NAD_STOCK}}$ can be estimated as $\tau_{\text{NAD_STOCK}} = b \cdot \text{VWC}_{\text{STOCK}}$, where b is a vegetation parameter and $\text{VWC}_{\text{STOCK}}$ is the vegetation water content of the vine stocks. In the literature, the values of b are in the range 0.10 - 0.12 [11, 13, 39]. Values of $\text{VWC}_{\text{STOCK}}$ were estimated by considering the stem density of 1/6 stocks m^{-2} , the moisture content of $0.5 \text{ m}^3 \text{m}^{-3}$, and the average weight of vine stocks varying between 4 kg and 6 kg. With these assumptions, the $\text{VWC}_{\text{STOCK}}$ is between 0.33 kg m^{-2} and 0.5 kg m^{-2} , and the resulting range of the effective optical depth of stocks is $0.033 \leq \tau_{\text{NAD_STOCK}} \leq 0.06$. These values are approximately half the optical depth τ_{NAD} retrieved for the vegetation winter state based on the L-band measurements. If the range $0.101 \leq \tau_{\text{NAD}} \leq 0.112$ given in Table 3 is treated as the actual optical depth, the corresponding “ground truth” value of the b -parameter for the vineyard in its winter state would be in the range of $0.20 \leq b \leq 0.34$.

During the summer state, the water content of the fully developed vegetation was estimated to be $1.63 \text{ kg m}^{-2} \leq \text{VWC} \leq 1.8 \text{ kg m}^{-2}$, to account for the different elements of the vine vegetation: stocks ($0.33 \text{ kg m}^{-2} - 0.5 \text{ kg m}^{-2}$), grapes ($\approx 0.8 \text{ kg m}^{-2}$), stems ($\approx 0.15 \text{ kg m}^{-2}$) and leaves ($\approx 0.35 \text{ kg m}^{-2}$). If $0.10 \leq b \leq 0.12$, the estimated range of optical depth $\tau_{\text{NAD}} = b \cdot \text{VWC}$ for the vegetation summer state is $0.163 \leq \tau_{\text{NAD}} \leq 0.216$. These values agree well with the corresponding “ground-truth” values of τ_{NAD} for the fully developed vegetation state given in Table 3.

Another approach to estimate τ_{NAD} of the fully developed vine vegetation follows from an approximate relation used in the L-MEB model: $\tau_{\text{NAD}} \approx b' \cdot \text{LAI}$, where b' is a vegetation

1 551 parameter (the default value used in L-MEB is $b' = 0.06$) and LAI is the Leaf Area Index. Two
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 3 552 experiments carried out at the MELBEX III vineyard in 2009 and 2010 using destructive and non-
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 6 553 destructive measurements (indirect optical estimations) converged to LAI yielded $2 \text{ m}^2 \text{ m}^{-2} \leq LAI$
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 8 554 $\leq 2.5 \text{ m}^2 \text{ m}^{-2}$ for several representative vines. Based on these estimates, the vegetation optical
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 11 555 depth of the fully developed vegetation is in the range $0.120 \leq \tau_{\text{NAD}} \leq 0.150$. However, the
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 13 556 empirical relation $\tau_{\text{NAD}} \approx b' \cdot LAI$ used was developed for crop fields, and thus does not include
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 16 557 any contributions from woody vine stocks. Nevertheless, the estimated range agrees well with
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 18 558 the measurement based τ_{NAD} shown in Table 3, and also with the range $0.130 \leq \tau_{\text{NAD}} \leq 0.156$
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 20
 21 559 estimated from the vegetation water content excluding vine stocks.

22
 23 560 Considering the “ground-truth” values of the tt^p parameters (Table 3), tt^v exceeds tt^h for both
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 25 561 vegetation states. These values indicate significant anisotropy of the vegetation, especially
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 28 562 during the winter state (isotropy would correspond to $tt^v = tt^h = 1$). It is likely that these anisotropic
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 30 563 effects can be related to the preferential orientation of the vine stocks in the vertical direction [13]
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 32 564 as the other vegetation elements (stems, grapes, leaves) having no evident preferential
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 35 565 orientation.

38 566 6. Summary and Conclusions

41 567 This study is the first to use data measured with one of the three identical ELBARA II
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 43 568 radiometer systems required by ESA and developed by Gamma Remote Sensing (Gümligen,
 44
 45
 46 569 Switzerland, <http://www.gamma-rs.ch/>) within the framework of the ESTEC contract
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 48 570 21013/07/NL/FF "L-band Radiometer Systems to be deployed for SMOS Cal/Val Purposes". The
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 51 571 corresponding multi-angular brightness temperatures were measured at the MELBEX III field
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 53 572 site, which is situated in a vineyard. This land-use type is typical of about 75% of the VAS area,
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 55 573 which is the Mediterranean validation and calibration site for SMOS retrievals. The study
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 58 574 presented general aspects of ELBARA II for field applications, as well as the retrieval of radiative
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 60 575 properties of vines based on ground-based L-band measurements in direct support of the
 576 ongoing SMOS calibration and validation activities at the VAS.

1 577 One major outcome of our study was the quantification of the absolute accuracy of ELBARA II
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3 578 measurements, which was shown to be better than ± 1 K for a wide range of the scene brightness
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6 579 temperatures measured. The short-term measurements (foil experiments), for which radiative
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8 580 contributions of the soil were largely eliminated, revealed radiative properties of the vines at
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10 581 different development states that compared well with estimates based on vegetation parameters
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13 582 observed directly in the vineyard. For the trimmed vines during the winter state, the retrieved b -
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15 583 parameter was in the range of $0.20 \leq b \leq 0.34$. This is at least twice as much as the range $0.10 \leq$
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18 584 $b \leq 0.12$ often found in the literature for low growing vegetation. This discrepancy has to do with
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20 585 the fact that vines in their winter state consist mainly of woody components, which is not the case
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22
23 586 for most of low growing vegetation types investigated so far. Hence, we recommend using the
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25 587 higher values of the b -parameter found in this study for comparisons with SMOS retrievals over
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27 588 the VAS area. The multiple scattering radiative transfer model applied in our analysis also
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29
30 589 improves the physical base of the L-MEB retrieval scheme. In the case of very moist soils below
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32 590 scattering vegetation, this model potentially improves SMOS level-2 retrievals, while including the
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34
35 591 same set of parameters as the zero-order non-coherent solution of the radiative transfer
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37 592 equations currently implemented in L-MEB.
38
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41
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43
44
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49
50 597 supporting the projects *Product Validation*, *Data Exploitation and Expert Center for the SMOS*
51
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53
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