Remote Sensing Techniques to Measure Dew: The Detection of Canopy Water with an L-Band Passive Microwave Radiometer and a Spectral Reflectance Sensor

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ABSTRACT

A technique to quantify the amount of dew on grassland with an L-band (1.4 GHz) passive microwave radiometer has been presented. The horizontal polarized brightness temperature is sensitive to dew and morning dew can increase the temperature up to 5 K. This is in contrary to recent published results, where they expect that dew does not have any effect on L band (1.4 GHz) observations.
By using both the horizontal and vertical polarized brightness temperature in combination with measured soil moisture conditions we were able to estimate the amount of dew. The results compared well with another remote sensing technique to measure dew using a spectral reflectance sensor.
In addition, the relationship between MPDI and internal vegetation water was defined and this relationship was significantly different than the dew MPDI relation and according to our experiment, the MPDI is more sensitive to external canopy water like dew, than internal canopy water.

Keywords: dew, passive microwave remote sensing, spectral reflectance, vegetation water content

1. INTRODUCTION

The occurrence of dew can be important in many environmental studies. Dew recharges the soil moisture and limits evaporation from the soil during the time the dew is forming.

In deserts dew can serve as a source of water for small animals, and plants (Jacobs et al., 2002). A study with Mediterranean shrubs and plants showed that plant leaves can absorb dew and thus restore plant water status (Munne-Bosch et al., 1999). Dew can also favor any plant pathogen, whose spores or cells require free water to germinate (Royle and Butler, 1986).

On a different note, dew can also have a significant effect on remote sensing sensors who observe the earth when dew is forming. In 1986 Pinter showed the effect of dew on spectral reflectances in the visible and mid infrared region, which can have serious implications for the satellite observations in these wavelength regions, like the morning scans of the Landsat satellites.

Passive microwave sensors are also sensitive to vegetation water and several current satellites such as the Special Microwave Imager (SSM/I) but also future sensors like the ESA's Soil

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Moisture Ocean Salinity (SMOS) mission and NASA's HYDROS will collect data when dew is likely.

According to several authors (Jackson and Moy, 1999, and Wigneron et al., 1996) dew should not have any effect on L band (1.4 GHz) observations and in extreme levels it may effect C band (5 GHz). The current research will show that this is not true. The objectives of the present study were to evaluate the effects of dew on the L-band observations and to quantify the dew density.

2. BACKGROUND

2.1 Microwave Theory

The theoretical basis for measuring vegetation water with microwave techniques is based on the large contrast between the dielectric properties of liquid water and dry vegetation. The large dielectric constant of water is the result of the water molecule's alignment of the electric dipole in response to an applied electric magnetic field (Engman, 1991).

The dielectric constants of water, air, soil, and vegetation are directly related to the emissivity of the surface. With a radiometer it is possible to measure the intensity of emission from a land surface. This emission is proportional to the product of the surface temperature and the surface emissivity which is commonly referred as the microwave brightness temperature (T_b).

The upwelling radiation as observed above a vegetation canopy may be given as a simple radiative transfer equation (Mo et al., 1982):

$$T_{bH} = T_s e_H \Gamma + (1-\Gamma)T_c(1-\omega) + (1-e_H)(1-\omega)T_c(1-\Gamma)\Gamma \quad (1)$$

$$T_{bV} = T_s e_V \Gamma + (1-\Gamma)T_c(1-\omega) + (1-e_V)(1-\omega)T_c(1-\Gamma)\Gamma \quad (2)$$

where the subscripts *H* and *V* indicate polarization, T_s and T_c are the thermodynamic temperatures of the soil and canopy, respectively, and ω is the single scattering albedo. The emissivities e_H and e_V are known (Fresnel) functions of the soil dielectric constant (*k*) and the incidence angle (*u*). The canopy transmissivity, Γ, is defined as

$$\Gamma = \exp\left(\frac{-\tau}{\cos u}\right) \quad (3)$$

where τ is the vegetation optical depth. The optical depth is a measure of how opaque a medium (in this case the canopy) is to radiation passing through it. The optical depth is related to the vegetation water content, and is also a function of the incidence angle, the radiometric frequency and is polarization dependence.

In this study we mainly use the Microwave Polarization Difference Index (MPDI), which is a ratio function between horizontal polarized brightness temperature and vertical polarized temperature and is defined as:

$$MPDI = \frac{T_{b[V]} - T_{b[H]}}{T_{b[V]} + T_{b[H]}} \quad (4)$$

The influence of soil and vegetation temperature on the MPDI is negligible, which is the main advantage of this index. Changes of this index are due to either vegetation changes or different soil moisture conditions.

3. FIELD EXPERIMENT

3.1 Study area

A field experiment was carried out from April 2003 till October 2003 at the weather station of the Meteorology and Air Quality Group of Wageningen University, located on the Haarweg in Wageningen, the Netherlands. The coordinates of the location are 51° 58' NB and 5° 38' OL and is about 7 meters above mean sealevel. The Haarweg meteostation is a special AgroMeteo-Station and the measurements include fluxes of energy, temperature, water and carbon dioxide. The data of this station can be obtained at www.met.wau.nl and a location map of the field site can be found in **Figure 1**. The experiment is described in detail in De Jeu and Owe 2003, and below the important instruments for this study are summarized

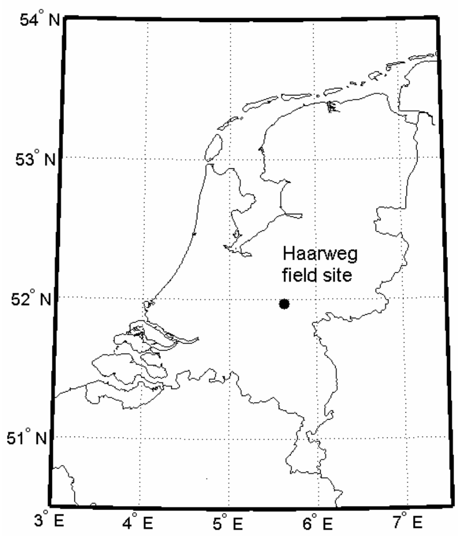

Fig. 1: The Haarweg meteorological field site located in Wageningen, the Netherlands

Date	Mowed Wet Biomass [kg m^{-2}]	Mowed Dry Biomass [kg m^{-2}]	Canopy Temp. [K]	Soil Temp at 5 cm depth [K]	Soil Moisture at 0-5 cm depth [m^3 m^{-3}]	ΔMPDI
May 8, 13:00 hr	0.106	0.032	297.6	288	0.31	0.033
May 22, 16:00 hr	0.169	0.028	289	287	0.44	0.057
June 12, 18:00 hr	0.192	0.054	296.1	295.5	0.25	0.044
July 31, 16:00 hr	0.360	0.115	310.3	296.1	0.11	0.074
Sept. 18, 13:00 hr	0.175	0.044	303.5	288.7	0.10	0.039

Table 1: The amount of mowed wet and dry biomass, temperature, soil moisture, and the change of MPDI after 5 mowing events of the short grass site.

3.2 Materials and methods

During the field experiment 3 different sites were measured simultaneously using an L-band passive microwave radiometer. One site was a bare soil site, one a grassland site which was mowed at a regular basis (referred as the short grass site) and one site was kept undisturbed (referred as the tall grass site). For this study we only used the short grass site. During the entire measuring period the grass site was mowed 5 times and the gathered mowed material was analyzed and summarized in **Table 1**. The soil under the vegetation is heavy river clay with a bulk density of 1.21 g m^{-3} and a porosity of 0.55 m^3 m^{-3}.

Fig. 2: The field setup of the leaf wetness sensor (small iron plate below) and the optical wetness sensor (sensor with aluminum foil in the center of the picture)

Within every 10 minutes the radiometer scanned the short grass with an average scanning time of 1 minute per site. The radiometer had an incidence angle of 52.5˚ which gave an ellipsoid footprint of about 5x8 meter on the surface. During this experiment we used different field instruments and a short description of the instruments which were not described in De Jeu et al. 2003 but were used in this paper are summarized below.

Leaf Wetness Sensor

The leaf wetness sensor detects the presence of surface moisture on foliage. When moisture is present, the sensor detects an electrical resistance change between the metal plated elements. This is displayed as a value between 0 (wet) and 1 (dry). In **Figure 2** a photo of the field set up with the leaf wetness sensor is presented

Spectral Reflectance Sensor

The Spectral Reflectance Sensor or Optical Wetness Sensor (OWS) is based on spectral reflectance spectroscopy. An all weather instrument that does not interfere with the wetting and drying process, and it is insensitive to solar radiation. The Optical Wetness Sensor (OWS) is able to detect minor changes in the intensity of the backscattered light in two narrow wave bands, one in a water absorption band (1930 nm) and the other one next to it (1700 nm). The last one acts as a reference. The band ratio is a measure of leaf water content.

The OWS emits a modulated broadband narrow beam of light and makes the sensor independent and immune to solar radiation. The OWS light source is collimated and projected onto a surface and the reflected radiant energy is collected and coupled back into an optical fiber. The input fiber equally splits the reflected light into two fibers. This concept ensures that both fibers are looking at the same surface. There are two light detectors that are optically coupled to these glass fibers. Two optical interference narrow bandpass filters with collimation optics, couple the light from the two fibers onto these detectors. By means of signal processing (lock-in amplifiers), the intensity of the reflected light can be recovered from the background noise (solar radiation). A limitation is that the wavelength of the absorption band (1.93um) limits its ability to look deep into a surface. **Figure 2** shows a photo of the OWS we used during our experiment.

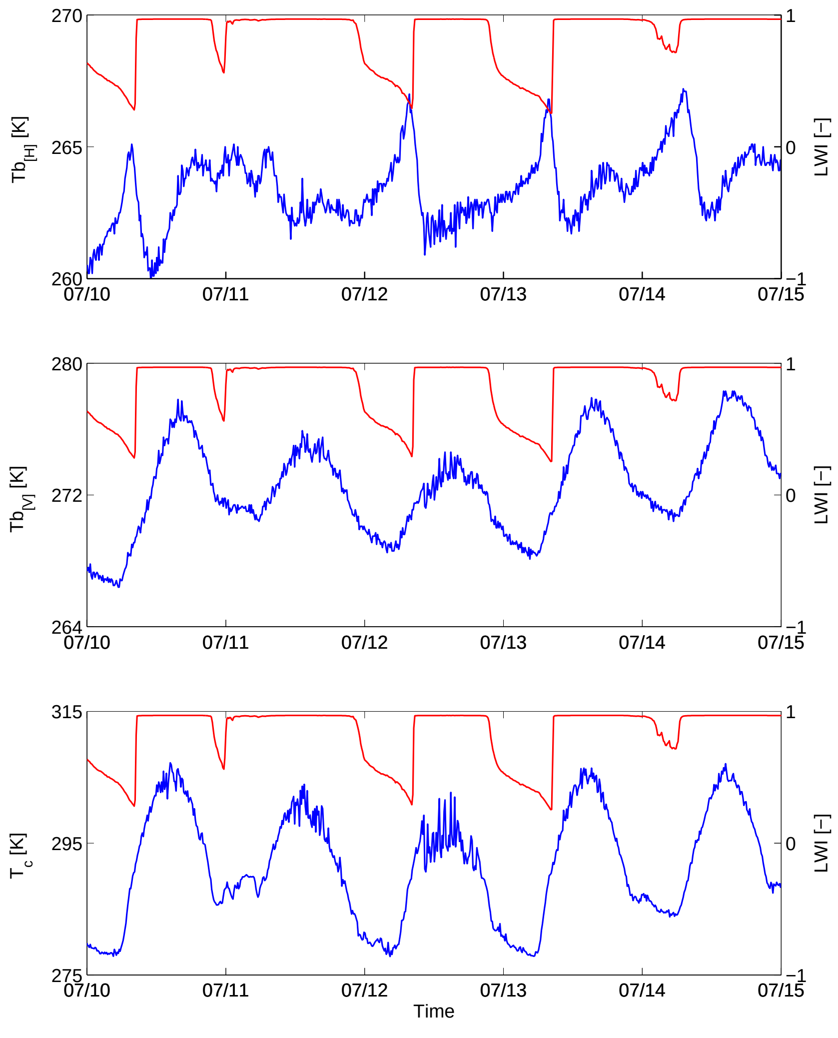

Fig. 3: The reaction of horizontal (top) and vertical (middle) polarized brightness temperature at L-band, and vegetation temperature (below) on morning dew, which was detected by the leaf wetness sensor (wet = 0, dry = 1). On a dew event on July 12 the horizontal brightness temperature increases 5 K.

4. RESULTS

4.1 Quantification of Dew

The effect of dew on the different temperature measurements are illustrated in **Figure 3**. In this figure five days in July (10-14 July 2003) are presented with 3 big dew events on July 10, 12 and 13. These events were detected with the leaf wetness sensor. It shows that the condensation starts at midnight till 8 o'clock in the morning, resulting in an increase of about 5 degrees Kelvin in the horizontal brightness temperature for the short grass. After 8 o'clock the condensation stops but the dew effect continues and disturbs the horizontal brightness temperature till 11 o'clock. No significant effect of dew can be found in the vertical brightness temperature or in the vegetation

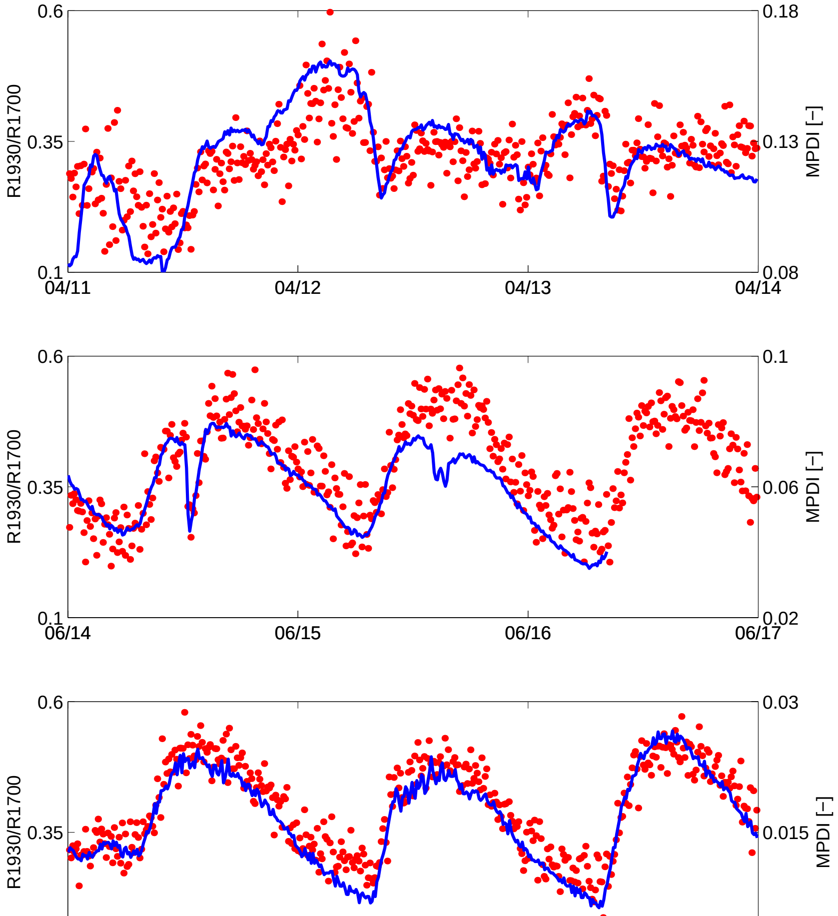

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Fig. 4: The diurnal variations of the MPDI as derived from the L-band radiometer (solid line) and the R1930/R1700 measurements of the optical wetness sensor (dots) for several days in April, June and July. Both independent sensors clearly show similar diurnal variations.

This is in agreement with previous findings of Owe et al. 2001, where they illustrated with simulations that the horizontal polarized emissivity above a canopy at C-band is much more affected to differences in vegetation optical depth (which is a direct function of the vegetation water content, see Eq. 3) than the vertical polarized brightness temperature.

The MPDI is a well known index that can be used to minimize the soil and canopy temperature influence in the brightness temperature. The MPDI is a ratio indexes between the vertical and horizontal brightness temperature (*i.e.* Eq. 4) and is therefore mainly a function of vegetation emissivity and soil moisture. In **Figure 4**, the MPDI is presented in time for 3 short periods in April, June, and July. During these three periods, the TDR's under the short grass vegetation did not record a significant diurnal pattern in the soil moisture of the first 5 cm, nor a significant change during the week. April was the wettest period starting with an average soil moisture value of 0.36 $m^3\ m^{-3}$ at April 11 till a value of 0.34 $m^3\ m^{-3}$ at April 14. June was more dry, ranging from 0.24 $m^3\ m^{-3}$ to 0.2 $m^3\ m^{-3}$ from 14 till June 17. July was extremely dry. The soil moisture content did not change significantly and was consistently 0.12 $m^3\ m^{-3}$ for the entire period.

These observations indicate that the diurnal differences in the MPDI are mainly a function of the diurnal changes of the vegetation water content.

In **Figure 4** the MPDI is compared to the R1930/R1700 ratio of the optical wetness sensor and it showed remarkable similarities. The absolute value and the diurnal amplitude of the MPDI is different for the three different periods, but all showed the same similar relative pattern as the OWS.

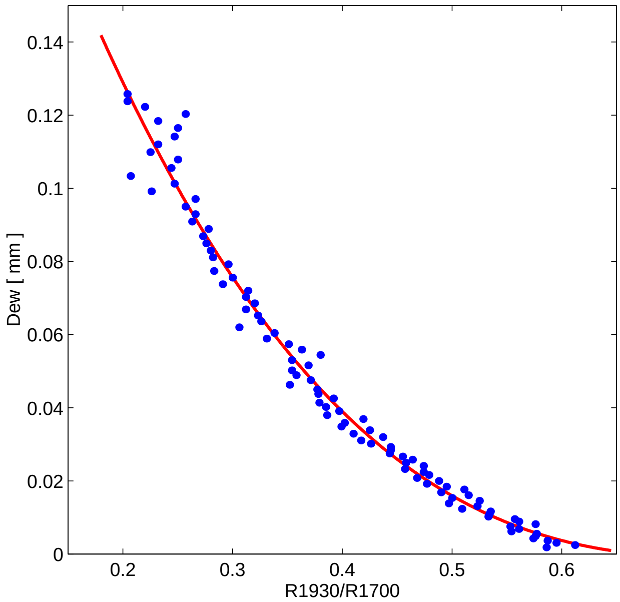

Fig. 5: Laboratory calibration of the Optical Wetness Sensor (OWS). Dots are measurements of dew. The dots represent the measurements, and the solid line the empirical model, as given in equation 6.

The OWS was calibrated in the laboratory with this grass type. We started with wet grass and we monitored the drying process with a weighting device and the OWS. The change of weight per certain area is an indication of dew loss and can estimated in mm. **Figure 5** shows the extreme high relationship (R^2 =0.98) between the OWS and dew. For this case we used the following simple third order polynomial function to estimate the amount of dew with the OWS:

$$Dew = -0.48 \cdot \left(\frac{R1930}{R1700}\right)^3 + 1.26 \cdot \left(\frac{R1930}{R1700}\right)^2 - 1.07 \cdot \left(\frac{R1930}{R1700}\right) + 0.30 \qquad (5)$$

where the dew is indicated in mm.

By using this new relationship, the optical ration R1930/R1700 can be converted to dew and the L band observations can be plotted with the dew measurements. In **Figure 6** we see three complete different relationships. It seems that the relationship between dew and MPDI is most pronounced when the soil is dry. When the soil is wet, there is much more scatter in the plot.

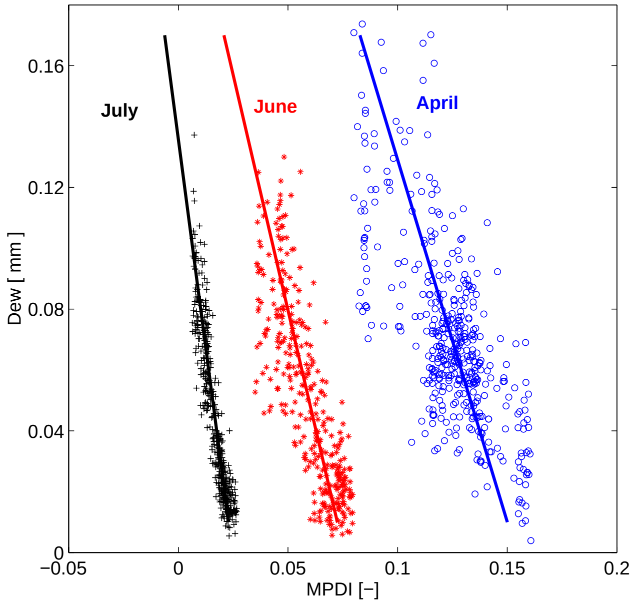

Fig. 6: The MPDI versus morning dew. There are different relations for different soil and vegetation conditions.

Using simple linear regressions, we can say that for

April (Soil Moisture of 0-5 cm = 0.35 ±0.006 m^3 m^{-3});

$$Dew = -1.143 \cdot MPDI + 0.213 \tag{6}$$

R^2=0.48, Standard error of the estimated Dew = 0.02 mm, n = 431

June (Soil Moisture of 0-5 cm = 0.22 ±0.01 m^3 m^{-3});

$$Dew = -2.033 \cdot MPDI + 0.171 \tag{7}$$

R^2=0.66, Standard error of the estimated Dew = 0.02 mm, n = 337

And July (Soil Moisture of 0-5 cm = 0.12 ±0.003 m^3 m^{-3});

$$Dew = -4.581 \cdot MPDI + 0.121 \tag{8}$$

R^2=0.84, Standard error of the estimated Dew = 0.01 mm, n = 432

The mutual differences of MPDI between the three periods may be explained by the differences in average soil moisture and biomass. It is still unclear why there is a bigger scatter in April compared to July and further research is necessary to understand this phenomenon.

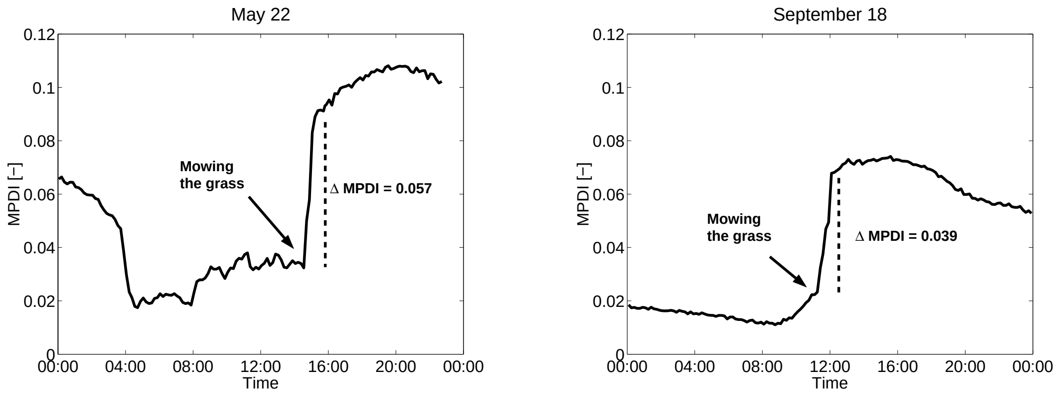

Fig. 7: The effect on MPDI during a mowing event on May 22 and September 18. Detailed information about these mowing events can be found in Table 1.

4.2 The quantification of internal vegetation water

During the field experiment 5 mowing events were registered. These mowing events can be used to give a first indication of the internal vegetation water content. Just before and after each mowing event the MPDI was calculated and the differences in MPDI (*ΔMPDI*) were used to compare with the vegetation water content. **Table 1** presents the results of these mowing events and the change vegetation water content (*ΔVWC*) can be defined as wet biomass minus dry biomass.

Figure 7 shows the effect of mowing on the MPDI for an event on May 22 and September 18.

With the inclusion of soil moisture it is possible to find a relationship between MPDI and VWC. Even if there are only 5 points, the relationship between VWC, MPDI and soil moisture is:

$$\Delta VWC = -3.316 \cdot \Delta MPDI + 0.155 \cdot SM - 0.020 \qquad (9)$$

ΔVWC is the change in vegetation water content in kg m^{-2}, and *SM* the soil moisture of the first 5 cm in m^3 m^{-3}. The R^2 was 0.99 for 5 points and the standard error of estimated VWC of 0.01 kg m^{-2}.

This relation is based only on 5 mowing events, and at these events the grass was always dry before mowing, indicating that there was no influence on the MPDI from external water (dew).

The MPDI-VWC is only based on internal vegetation water whereas the dew-MPDI relation is only based on external water. With a simple example we are able to compare the sensitivity of MPDI on internal (VWC) and external vegetation water (dew). According to equation 9, during the studied April period, the MPDI will change …. when we change the VWC 0.1 kg m^{-2} (~0.1 mm Dew). For this same period a the MPDI will change when there is a dew event of 0.1 mm.

This indicates that the effect of external water (or dew) on the microwave emission is much stronger than the internal water. The other two periods June and July confirm this hypothesis where *ΔMPDI* is respectively .. and .. for a *ΔVWC* of 0.1 kg m^{-2} compare to the values of .. and .. for a 0.1 mm dew event.

5. CONCLUSIONS/DISCUSSION

According to the published results and the well-documented levels of dew deposition, dew should not have any effect on L band (1.4 GHz) observations (Wigneron et al 1996; Jackson and Moy, 1999). However, during our experiment there was a strong effect of dew on the horizontal polarized microwave signal. Moreover, we were able to use the signal to detect, and quantify the amount of dew. The effect of dew on the horizontal polarized brightness temperature was often a 5 K increase. The condensation usually started at midnight till 08:00 hr and the grass was wet till 11:00-12:00 hr.

By using an optical wetness sensor we were able to quantify the amount of dew and the diurnal pattern of this instrument was similar as the diurnal pattern of the microwave polarization difference index, indicating that there is a strong relationship between dew and microwave emission. During this study we discovered a relationship between MPDI and dew and it seems that this relationship is sensitive to the soil moisture conditions, biomass, and vegetation structure.

In our case we found three different relationships for three different soil conditions. For all three periods the amount of dew was 0.1 mm on average. For dry conditions, the relationship between dew and MPDI was the best with the lowest scatter and a R^2 of 0.84. A good explanation for this phenomenon is still missing and further research is necessary to understand this behavior.

The relation between internal water or vegetation water content (VWC) and microwave emission at L-band was also studied. Five mowing events showed different increases in MPDI and a simple empirical relationship was applied between the difference in MPDI, soil moisture conditions and the mowed vegetation water content (mowed wet biomass – mowed dry biomass). The correlation coefficient was very high ($R^2 = 0.99$) which gave us some confidence in the relationship, even when we just used 5 points.

A simple comparison study was done to study the sensitivity of the microwave emission on dew events and changes in internal water. It seems that the microwave emission at L band is much more sensitive to changes in dew than to changes in vegetation water content, especially when the soil is wet.

This new result gives us a new insight in the behavior of microwave emission on dew, and these results show that we can not ignore the effect of dew on passive L-band observations.
This new results can be of major importance for the land surface retrieval algorithms for the future SMOS and Hydros L-band satellite missions, because they will scan the earth surface when dew is most likely round 06:00 hr solar time.

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