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Title: High-resolution mapping of in-depth soil moisture content through a laboratory experiment coupling a spectroradiometer and two hyperspectral cameras

Authors: A. Bablet^{a,b}, F. Viallefont-Robinet^{a,*}, S. Jacquemoud^b, S. Fabre^a, X. Briottet^a

^a ONERA/DOTA, Université de Toulouse, 2 avenue Edouard Belin, BP 74025, 31055 Toulouse Cedex 4, France (aurelien.bab@gmail.com, francoise.viallefont@onera.fr, sophie.fabre@onera.fr, xavier.briottet@onera.fr)

^b Université de Paris, Institut de physique du globe de Paris, CNRS, F-75005 Paris, France (jacquemoud@ipgp.fr)

* corresponding author

Keywords: Hyperspectral remote sensing; Soil moisture content; High-resolution water vertical profile; MARMIT model

Highlights:

- A lab experiment is designed to measure surface and in-depth soil reflectance
- The MARMIT model is used to associate surface moisture content to reflectance
- Vertical maps of soil moisture content are generated on clay loam and sandy soils
- The corresponding profiles are calculated for both soils
- Their evolution over time is analyzed

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Abstract

A laboratory experiment is set up to study both surface and in-depth soil moisture content (SMC). For that purpose, an aquarium is filled successively with two soils, a clay loam and a sand. Reflectance spectra are acquired in the solar domain (400-2400 nm) on the soil surface using an ASD FieldSpec 3 HR spectroradiometer and in-depth through the aquarium glass wall using two hyperspectral cameras. Successive amounts of water ranging from low to heavy rainfall in a temperate region are uniformly poured into the aquarium. The MARMITforSMC method based on the MARMIT (*Multilayer Radiative Transfer Model for soil reflectance*) model is applied to each reflectance spectrum to determine gravimetric SMC. In particular, vertical profiles of SMC are provided with unprecedented spatial accuracy (~0.287 mm). The results are compared with volumetric SMC measured by two time-domain reflectometry (TDR) sensors. The in-depth SMC image produced on the sand shows lower values within the first 2cm (5%) than below (17%). In contrast, the SMC image produced on the clay loam shows evenly distributed values whatever the position in the aquarium, even 1h after moistening. The difference in grain size between the soils explains this result.

41 1. Introduction

42 Soil moisture content (SMC) is an important variable of the critical zone (Folke et al., 2004) that
43 plays a key role in weather and climate predictions by controlling exchange and partitioning of water,
44 gas, and energy fluxes between the land surface and the atmosphere (Vereecken et al., 2008; Kornelsen
45 and Coulibaly, 2014). Accurate estimation at various spatial and temporal scales is also important for
46 strategic management of water resources (Vereecken et al., 2016), flood prediction (Ochsner et al.,
47 2013; Schreiner-McGraw et al., 2016), drought monitoring (Bolten et al., 2010) and yield forecasting
48 (de Wit and van Diepen, 2007) in agriculture. However, SMC greatly varies in time and space due to
49 inherent variations in soil hydraulic properties (Montzka et al., 2011), precipitation rates (Koster et al.,
50 2004; Rosenbaum et al., 2012), topography (Joshi and Mohanty, 2010; Jana and Mohanty, 2012;
51 Schröter et al., 2015), and vegetation characteristics (Famiglietti et al., 1998; Gaur and Mohanty, 2013).
52 Depending on the wavelength range, remote sensing is likely to provide information about surface or
53 in-depth water content. Indeed, in the solar domain, sunlight only penetrates through the first
54 micrometers or millimeters of the soil (e.g., Perkins, 1963; Woolley and Stoller, 1978; Tester and
55 Morris, 1987; Liang et al., 1997; Ciani et al., 2005), thus the information collected is surface SMC.
56 According to the frequency, microwaves go deeper into the ground, thus the information collected is
57 volume SMC. In situ measurements generally also correspond to volume SMC. Both surface and
58 volume SMC are valuable information, according to the application, but the remote sensing community
59 has seldom jointly studied them because the two wavelengths domains are separated in terms of signal
60 processing. Sadeghi et al. (2017) pioneered the measurement of high-resolution soil water content
61 profiles over seven soils covering a wide range of textures. They set up a laboratory experiment
62 involving a broadband camera operating in the shortwave infrared (900-1700 nm) and a novel TDR
63 array. They applied a relationship derived from the Kubelka-Munk theory to study water flux profiles
64 with an unprecedented accuracy.

65 This article presents a laboratory experiment imagined nearly at the same period to assess both
66 surface SMC and in depth SMC profiles thanks to a spectrometer, two hyperspectral cameras, and a
67 radiative transfer model called MARMIT (Bablet et al., 2018). We poured controlled amounts of water
68 on two different soils and measured the evolution of the SMC profiles with high spatial resolution.
69 Section 2 presents the laboratory experiment and the calibration of the radiometric data. In Section 3,
70 the spectral reflectance of the soils measured on the surface is compared to the one imaged on the side
71 of the aquarium; we also quantify the evolution of the SMC in time thanks to the MARMITforSMC
72 method. The results are discussed in Section 4.

73 2. Material, measurements and processing

74 2.1. Experimental set-up

75 As a first trial, two different soils, a clay loam and a sand, have been selected for this experiment.
76 Their main characteristics are summarized in Table 1. Although the fraction passing a 2 mm sieve was
77 collected for each soil, the sand was mostly composed of large white grains of homogeneous size while
78 the clay loam consisted of smaller brown grains of heterogeneous sizes. Both soils were successively
79 poured into an aquarium (dimensions: 27.5 cm long $\times$ 13 cm wide $\times$ 20 cm high) with glass walls 1.5
80 cm thick in their center, the corners being slightly thicker than the faces. The aquarium was put on a
81 linear motion platform.

82 **Table 1.** Some characteristics of the soil samples.

Soil sample	Texture			Composition	Bulk density
	Clay	Silt	Sand		
Clay loam	35.8 %	40.3 %	23.9 %		
Sand	0 %	0 %	100 %	SiO ₂ (98.5 %)	1.5 g cm ⁻³

83
84 The spectral radiance was measured from above (surface measurement) and from one side of the
85 aquarium (in-depth measurement). An ASD FieldSpec 3 HR spectroradiometer equipped with a 5°
86 aperture lens was used for the nadir acquisitions. The detector being located at a distance of 37 cm from
87 the soil, the footprint is a disk of about 3.2 cm in diameter. Two halogen lamps positioned on each side

88 of the spectroradiometer lit the soil from above with an incidence angle of 10°. A third halogen lamp lit
 89 the side of the aquarium. Two hyperspectral cameras fixedly positioned in front of the aquarium were
 90 used for the lateral acquisitions. They measure the radiance of a vertical pixel line in the visible-near
 91 infrared (HySpex VNIR-1600) and in the shortwave infrared (HySpex SWIR-320m-e). The pixel size
 92 of the VNIR camera is 0.06 mm × 0.12 mm while that of the SWIR camera is 0.287 mm × 0.287 mm.
 93 The two cameras imaged the scene line-by-line while the aquarium passed in front of them, like a push-
 94 broom scanner. The images consist of 720 vertical lines in the VNIR and 360 vertical lines in the SWIR.
 95 Their co-registration was helped by small pieces of duct tape on the outer glass wall of the aquarium. A
 96 common area 10.2 cm long and 9.1 cm wide was finally delimited to study the water profiles. The
 97 experimental setup is illustrated in Fig. 1 and a summary of the main characteristics of the optical
 98 sensors is provided in Table 2.

Fig. 1. Experimental set-up showing the two hyperspectral cameras, the spectroradiometer, the two lamps illuminating the soil from above, and the aquarium on the linear motion platform.

Table 2. Main characteristics of the optical sensors.

Sensor	Spectral range (nm)	Spectral sampling interval (nm)	Number of spectral bands	Aperture angle (°) or field of view (mrad)
ASD	350-2500	1.4-2	1512	5°
VNIR camera	414-992	3.7	160	0.18 mrad
SWIR camera	966-2500	6	256	0.75 mrad

102 Finally, after each scan, two TDR (*Time Domain Reflectometry*) probes were inserted in the soil from
103 above to measure volume moisture content at two different depths: the Trime-Pico 64/32 probe (5 cm
104 long pins) and the FieldScout TDR 100 probe (3.7 cm long pins). According to the user manuals, soil
105 moisture is detected up to a distance of 3 cm around the pins, which corresponds to a surveyed cylinder
106 shape volume of 141 cm³ for the Trime-Pico probe and 104.6 cm³ for the FieldScout TDR. These values
107 are to compare to the volume of the aquarium that is 7150 cm³. The probe accuracy provided by the
108 manufacturers is $\pm 3\%$ moisture by volume.

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110 **2.2. Measurement protocol**

111 The measurements are carried out in four stages:

112 1) A known amount of water is uniformly and softly poured onto the soil using a plastic box
113 drilled with 2 mm diameter holes. It limits the change in appearance of the soil surface, and it
114 prevents water from flowing along the walls of the aquarium. After moistening, the aquarium is
115 put back on the linear motion platform in exactly the same position.

116 2) The radiance spectrum of the soil surface is measured with the ASD spectroradiometer. Each
117 spectrum is actually an average of 50 spectra. During acquisition, the lamp illuminating the
118 aquarium from the side and used for the HySpex measurements is obscured by an opaque shield.

119 3) Hyperspectral images of the soil are acquired with the line-scan HySpex cameras by translating
120 the aquarium laterally.

121 4) The two TDR probes are then inserted into the soil at one side of the aquarium to measure
122 volumetric soil moisture content.

123 Once the cycle is over, a given amount of water (~100 g) is added and new measurements are
124 performed (steps 1 to 4) after the water front stabilizes. A total of nine cycles of measurements were
125 made corresponding to the dry soil plus eight moisture levels (Table 3). The waiting time between two
126 cycles was much longer for the clay loam soil (up to 50 minutes) than for the sandy soil (up to 15
127 minutes) so the duration of one cycle varies according to soil type and moistening level. The water mass
128 (g) was translated into rainfall values (mm) for comparison with natural precipitations. For instance,

Météo-France, the French national meteorological service, indicates a monthly cumulative rainfall of 55 mm in Paris: a light rain corresponds to a rainfall of 1 to 3 mm h⁻¹, an average rain to a rainfall of 4-7 mm h⁻¹, and a heavy rain to a rainfall of 8 mm h⁻¹ or more. During extreme events, these values may exceed 100 mm h⁻¹. The quantities of water poured into the aquarium during our experience consequently ranged from light to heavy rainfalls in a temperate region.

Table 3. Quantity of water poured over the two soils at each moistening stage. Δt is the elapsed time between the addition of water and the measurement with the cameras.

Moisture level	Clay loam				Sand			
	Δt (min)	Added water mass (g)	Cumulative water (g)	Cumulative water (mm)	Δt (min)	Added water mass (g)	Cumulative water (g)	Cumulative water (mm)
#1	18	96.5	96.5	2.7	9	100.3	100.3	2.8
#2	8	98.2	194.7	5.5	8	105.9	206.2	5.8
#3	9	108.2	302.9	8.5	7	99.1	305.3	8.5
#4	16	99.6	402.5	11.3	6	107.0	412.3	11.5
#5	17	115.3	517.8	14.5	10	112.5	524.8	14.7
#6	14	127.2	645.0	18.1	10	101.1	625.9	17.5
#7	48	180.1	825.1	23.1	12	109.6	735.5	20.6
#8	50	208.1	1033.2	28.9	15	209.7	945.2	26.5

2.3. Data pre-processing chain

Data production requires a series of pre-processing operations. The first step is the coregistration of the VNIR and SWIR images acquired by the two cameras in order to cover the entire reflective domain. Their instantaneous fields of view are different, so are the spatial resolutions of the images. Thus, pre-processing begins with the degradation of the spatial resolution of the VNIR image in order to match that of the SWIR image. This resampling is achieved by using the nearest neighbor filter that preserves the spectral information. The two images are then co-registered using GeFolki, a multi-scale registration software developed by ONERA that exploits the few overlapping spectral bands between the two images (Brigot et al., 2016). It results in a hyperspectral data cube containing 320×300 pixels with a side length of 0.287 mm (9.1 cm $\times$ 8.5 cm image) in the reflective domain. Each pixel contains a continuous radiance spectrum made of 408 narrow bands between 414 nm and 2400 nm (Fig. 2). The spectral sampling is 3.26 nm for the VNIR camera and 5.45 nm for the SWIR camera. The last eight spectral bands of the VNIR camera, also measured by the SWIR camera, are removed in order to avoid spectral domain overlap. Fig. 2 displays the radiance of a pixel extracted from the dry sand image.

Fig. 2. (Left) image of the dry sand in the aquarium obtained with the HySpex cameras at 966 nm with the pieces of duct tape in grey and (right) radiance spectrum of a pixel of the image expressed in $\text{W m}^{-2} \text{sr}^{-1} \mu\text{m}^{-1}$.

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A jump in the radiance spectrum is clearly visible at the wavelength of 966 nm corresponding to the boundary between the VNIR and SWIR images (Fig. 2). That problem, common in radiometry, is expected to disappear when calculating the reflectance factor of the soil-aquarium system:

$$R_{s-a} = \frac{L_{s-a}}{L_{rp}} \times R_{rp} \quad (1)$$

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with R_{s-a} and L_{s-a} the reflectance and the radiance of the soil-aquarium system, R_{rp} and L_{rp} the reflectance and the radiance of the reference panel (Spectralon®). The relevant quantity is nevertheless the soil reflectance. To remove the contribution of the aquarium glass wall, we placed a sheet of white paper, the optical properties of which are known, successively inside and outside the aquarium. To first order, the transmittance of the aquarium glass wall equals:

$$\tau(\lambda) = \frac{R_{paper+glass}}{R_{paper}} \quad (2)$$

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with $R_{paper+glass}$ and R_{paper} respectively the reflectance of the paper behind and in front of the glass wall. Fig. 3 shows the spectral variation of $\tau(\lambda)$.

Fig. 3. Spectral transmittance τ of the aquarium wall.

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170 Then each reflectance spectrum of the soil-aquarium system is divided by $\tau(\lambda)$ to calculate the soil
 171 reflectance only. However, although reduced after conversion to reflectance and correction of the
 172 aquarium transmittance, the jump at 966 nm was still noticeable (**Fig. 4**). This artifact may have several
 173 causes including camera instability or non-nominal shutter operation of one of the two cameras. To
 174 remove it, we compared the reflectance of the dry sand acquired vertically with the ASD with that
 175 acquired laterally with the cameras. The sand was used rather than the clay loam because the grain size,
 176 which is known to control soil reflectance (e.g., [Okin & Painter, 2004](#); [Sadeghi et al., 2018](#)), is more
 177 homogeneous. **Fig. 4** shows a good agreement in the SWIR but an overestimation of the reflectance
 178 spectrum by the HySpex VNIR camera. According to the pixel, this overestimation varies between 0%
 179 and 5%. Therefore, the reflectance ratio C defined as

180

$$C = \frac{R(\lambda = 963.3 \text{ nm})}{R(\lambda = 966.7 \text{ nm})} \quad (3)$$

181

182 is calculated for each pixel of the image at the junction between the two cameras and the VNIR spectrum
 183 is divided by C to obtain a continuous spectrum (**Fig. 4**). This pre-processing is a prerequisite for
 184 analyzing the spectra acquired by the HySpex cameras.

185

Fig. 4. Uncorrected reflectance spectrum of the sand acquired by the cameras compared to the reflectance spectrum acquired on the surface by the ASD and to the corrected spectrum of the same soil in the aquarium.

3. Results

3.1. Reflectance analysis

3.1.1 Stability

The impact on the reflectance of a variation in illumination during the experiment was first assessed. Two phenomena are likely to occur: 1) a drift of the luminous intensity of the lamps, and 2) a variation of the ambient light of the laboratory that was in the half-light. These effects can be theoretically corrected by regular measurements of the radiance of the Spectralon® panel but, due to experimental constraints, only one spectrum was acquired at the beginning of the experiment. In order to appraise this impact, we considered a deep zone in the sand that remains dry from measurements #1 to #5 (Fig. 5a), as well as one of the three pieces of duct tape (Fig. 5b). In both cases, the change in reflectance was less than 4%.

Fig. 5. Reflectance variations of (a) dry sand and (b) duct tape at moisture levels #1 to #5.

3.1.2 Vertical variation

The change in soil reflectance as a function of depth provides us with information on its variation in relation to surface reflectance. To study that relationship, we divided the images into twenty contiguous rectangles (78 pixels $\times$ 15 pixels) having the same surface area (2.24 cm $\times$ 0.43 cm) as illustrated by **Fig. 6**.

Fig. 6. Representation of the twenty rectangles on the RGB image of the dry clay loam. The dark blue rectangle, referred as Zone 1, is the closest to the surface while the yellow rectangle, referred as Zone 20, is the farthest. In light grey, the three pieces of duct tape.

Prior to comparing the reflectance of wet and dry areas, one can analyze the reflectance of the dry soils. **Fig. 7** superimposes the reflectance spectrum of the surface on the average reflectance spectrum measured in each layer. The variability of dry soil reflectance is higher for the clay loam than for the

210 sand, probably due to a larger range of grain size. For the various moisture levels, the differences in
211 reflectance levels can be only attributed to soil water content since the other soil properties influencing
212 reflectance (mineralogical composition, organic matter, texture, homogeneity ...) are invariant during
213 the experiment. For the clay loam, the lowest reflectance spectrum that corresponds to the wettest soil
214 layer remains close to the surface and it matches closely the ASD reflectance spectrum. For the sand, it
215 is found deeper in the aquarium as water is poured in.

216

Fig. 7. Average reflectance spectra of the twenty rectangular zones for the dry and wet soils at moisture levels #2, #5, and #8. In dark blue, the closest to the surface (Zone 1) and in yellow, the farthest (Zone 20). On the left, the clay loam and on the right, the sand.

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We also plotted the standard deviation of the reflectance of all pixels in a zone (Fig. 8). It is higher for the dry clay loam (8% maximum for Zone 12) than for the dry sand (3% maximum for Zone 3). One

220 can also note that it is lowest at high moisture levels (saturated soil). In the transition zones where the
221 soil is partially wet, it is higher for the sand than for the clay loam, suggesting that the distribution of
222 water in the sand is highly variable within the same zone. The changes in reflectance due to the
223 penetration of water into both soils are analyzed qualitatively. To go further, the next section will focus
224 on soil moisture variation during infiltration.

225

Fig. 8. Standard deviation of the reflectance spectra in the twenty rectangular zones for the dry and wet soils at moisture levels #2, #5, and #8. In dark blue, the closest to the surface (Zone 1) and in yellow, the farthest (Zone 20). On the left, the clay loam and on the right, the sand.

3.2. Water content and moisture profile estimation

3.2.1 The MARMIT model and the MARMITforSMC approach

MARMIT is a radiative transfer model that simulates the reflectance spectrum of a wet soil in the solar domain assuming that the reflectance spectrum of the dry soil is known (Bablet et al., 2018). It considers a wet soil as a dry soil covered with a thin film of water characterized by two parameters: the thickness of the film L and the efficiency ε defined as the proportion of the ground covered by water. These two parameters are retrieved by fitting MARMIT to the measured reflectance spectrum. A calibration of the model is required for each soil: it consists in measuring reflectance spectra at various SMC and in linking SMC and the mean water thickness $\varphi = L \times \varepsilon$ by a sigmoid function (Fig. 9):

$$SMC_{clay\ loam} = \frac{45.3}{1 + 9.4 \times e^{-403 \times \varphi}} \quad (4)$$

$$SMC_{sand} = \frac{23.6}{1 + 9.0 \times e^{-39.4 \times \varphi}} \quad (5)$$

Fig. 9. Variation of SMC as a function of the mean water thickness for the clay loam and the sand. The lines correspond to Eqs. (4) and (5) respectively.

Note that the soil samples used in this calibration phase were placed in Petri dishes 1 cm deep, therefore, the estimated SMC is strictly speaking not a surface attribute but actually a volume attribute. Thanks to Eqs. (4) and (5), one can map SMC in the aquarium using the hyperspectral cameras, and at the same time, assess SMC on the soil surface using the ASD spectroradiometer. These two quantities have never been measured simultaneously before.

3.2.2 Check for consistency

Applying Eqs. (4) and (5) for the aquarium experiment implies that the water distribution is the same as in the Petri dishes. Moreover, since the measurement protocols differ in the two experiments (illumination angle and distance of the sensors from the soil sample), it is imperative to verify that the reflectance spectra of the dry soils are similar both for the calibration and experiment samples. A difference up to 10% is observed for the clay loam (Fig. 10a), while they match closely for the sand (Fig. 10b). The discrepancy is more important in the near-infrared and in the short-wave infrared than in the visible region of the electromagnetic spectrum. It has been shown that the influence of the grain size on reflectance is minimum in the visible and maximum in the infrared (e.g., Okin and Painter, 2004; Sadeghi et al., 2018). We conclude from this that the differences in reflectance for the clay loam are probably due to inhomogeneities in the grain size, and that the protocol has little or no influence on the measured reflectance.

Fig. 10. Differences between the spectral reflectances acquired with the ASD for soil in the Petri dish and in the aquarium (dash-dot line in Fig. 7) for (a) the dry clay loam and (b) the dry sand.

3.2.3. SMC maps and profiles versus TDR measurements

The input parameters L and ε of MARMIT are first estimated by inversion of the model on the soil reflectance spectra acquired both on the surface and the side of the aquarium. Then, the values of $\varphi = L \times \varepsilon$ are injected into Eqs (4) and (5) to calculate SMC (Figs 11 and 12). The estimation error is about 3% (Bablet et al., 2018). Note that the calibration equations linking SMC and φ do not necessarily pass

through the origin (Fig. 9), which may lead to uncertainties for low water content ($SMC < 5\%$ for the clay loam and $SMC < 3\%$ for the sand). Water content profiles are then easily obtained by averaging the SMC values on each horizontal pixel line of the hyperspectral images. The integrated values of soil moisture content (SMC_i) determined using the water content maps can be compared with the values measured by the FieldScout TDR 100 (SMC_{fs}) and the Trime-Pico 64/32 (SMC_{tp}) probes just after the radiometric measurements. These measurements enable us to assess integrated SMC between 0 and 3.7 cm and between 0 and 5 cm, respectively (Table 4). The values of the two probes agree for the clay loam but are somewhat different for the sand. Such a difference was expected but the evolution of the measurements with the successive “rain falls” doesn’t follow the increase and decrease suggested by the profiles, with a decrease occurring earlier for the FieldScout. Moreover, there is no apparent relationship between SMC_i and the probe measurements. Their representativeness may be poor in such a context due to the successive driving and digging up of the probes, which disturb the soil layers. These effects may vary from one soil to another.

The profiles extracted from the images agree with the literature: after moistening, water is evenly distributed in the clay loam when the sand displays a wide disparity, as noticed by Edwards et al. (2013). At the highest moisture level (#8), SMC is less than 5% in the first 2cm of the sand whereas it equals 17% on average below. For the clay loam, the water content equals 45% at surface and at depth when the soil is saturated with water.

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Table 4. Volume soil moisture content ($\text{cm cm}^{-3} \times 100$) measured by the two TDR probes: SMC_{fs} for the FieldScout TDR 100 (3.7 cm pins) and SMC_{tp} for the Trime-Pico 64/32 (5 cm pins).

Moisture level	Clay loam		Sand	
	SMC_{fs}	SMC_{tp}	SMC_{fs}	SMC_{tp}
Dry soil	0.0	0.3	0.0	0.3
#1	8.4	4.3	1.9	1.3
#2	13.8	12.2	2.2	5.1
#3	28.0	29.9	3.1	6.5
#4	34.3	32.5	5.4	17.0
#5	35.7	37.2	5.1	21.5
#6	36.5	38.9	4.8	18.7
#7	37.0	39.0	4.5	19.1
#8	40.0	44.5	4.6	20.7

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Fig. 11. SMC maps of the clay loam as a function of the amount of water poured and associated water content profiles. From top left to bottom right: moisture levels #1 to #8 (Table 2). S = piece of duct tape. The star points the SMC value measured at the top of the soil.

Fig. 12. SMC maps of the sand as a function of the amount of water poured and associated water content profiles. From top left to bottom right: moisture levels #1 to #8 (Table 2). S = piece of duct tape. The star points the SMC value measured at the top of the soil.

286 **4. Discussion**

287 The water front takes longer to stabilize in the clay loam than in the sand, therefore the time elapsed
288 between the addition of water on the soil and the radiance measurement is higher for the first soil (~50
289 minutes max) than for the second one (~15 minutes max) (Table 3). One reason is that water penetrates
290 faster in the sand. This agrees with Darcy's law that describes the flow of a fluid through a porous
291 medium. It stipulates that the hydraulic conductivity K is much higher in coarse-grained soils (e.g., the
292 sand) than in small-grained soils (e.g., the clay loam) due to the large intra-granular distance. Capillary
293 forces are very low and the force of gravity prevails, so water tends to infiltrate without stagnating.
294 Therefore, movement of water across the sand is much faster. On the contrary, in a clay loam soil, the
295 capillary forces that are greater due to the short intra-granular distance counterbalance the gravitational
296 forces applied on the water. In short, water naturally seeps into the sand and it penetrates into the clay
297 only because of the increased pressure due to the addition of water to the water column. Another reason
298 may be evaporation that dries the surface: the first stage occurs earlier for the sand than for the clay
299 loam (e.g., Han and Zhou, 2013; Or et al., 2013; Song et al., 2014; Merz et al., 2014). However, only
300 the capillary force explains the observations at a depth of 2 cm or below for the sand in such a short
301 time.

302 The link between the hydraulic conductivity and the grain size may also explain the high standard
303 deviation values in the sand (Fig. 8): for example, at moisture level #5, one can see rapid variations in
304 SMC at about 4.5 cm depth. This anomaly is certainly linked to a different particle size in this zone.
305 Indeed, the larger the grains, the greater the percolation. Therefore, SMC is smaller in this area.

306 Another issue concerns the deep pixels where a non-zero SMC is predicted while water did not arrive
307 at this depth yet (see SMC #1 in Fig. 11). These pixels may correspond to pores in the dry soil, which
308 create shadows that decrease the reflectance. Note that soil compaction is also likely to occur between
309 two experiments, either because the aquarium is moved meanwhile, or because of the moistening itself.
310 The model assimilates such low-reflectance pixels to a wet soil.

For the sand, we also noticed that SMC determined with the ASD spectroradiometer did not exactly match SMC determined with the HySpex cameras at the top of the profile (Figs 11 and 12). This difference is due to the unevenness of surface moistening: the central part of the aquarium is wetter than the edges, where water infiltration is monitored by cameras. In addition, SMC at the top of the soil is difficult to determine accurately from the images.

Despite the issues mentioned, with regard to water content profiles, we recognize the three regimes that have been identified by Al-Hamdan and Cruise (2010):

- 1) the soil has just been watered, it is wet on the surface but dry in depth (moisture levels #1 to #7 for the loam clay and moisture level #1 for the sand);
- 2) water has entered into the soil, which is dry on the surface but wet in depth (moisture levels #6 to #8 for the sand);
- 3) the soil is still dry in depth, but and has become dry again on surface after infiltration or evaporation (moisture levels #2 to # 4 for the sand).

Such a dynamic (or transitional) regime typically occurs several hours after a rain.

Various techniques can be used in the laboratory to assess soil moisture profiles. Sadeghi et al. (2017) who reviewed the most common ones (X-ray micro-computed tomography, neutron radiography, and magnetic resonance imaging) explain that optical methods are easier, faster, and cheaper to implement. In particular, the spatial resolution is higher for equal soil volume. Moreover, our experiment enables to assess surface and in-depth SMC nearly simultaneously.

If the soil physical parameters are available, profile can also be computed thanks to theoretical hydrological models such as the HYDRUS computer software packages (Šimůnek et al., 2016). Although this approach is a powerful way to connect surface and subsurface SMC in a large number of cases, it is beyond the scope of this article. However, our experiment provide specialists with unique experimental data to run such models.

336 5. Conclusion

337 We designed a new experiment to measure simultaneously soil surface reflectance and soil in-depth
338 reflectance, and to study their evolution over space and time while pouring water onto a soil. We used
339 the MARMITforSMC method to obtain high spatial resolution maps of SMC and the associated water
340 profiles. We observed profiles commonly described in the literature, but with a spatial resolution rarely
341 achieved.

342 As observed of [Edwards et al. \(2013\)](#) on sand, surface SMC is much lower than SMC at 3 cm depth
343 about 15 to 20 min after a heavy rainfall (20-30 mm). For the clay loam, water penetrates uniformly
344 into the soil. We also tried to compare the SMC profiles with measurements provided by TDR probes.
345 While the agreement is good for the clay loam, there are discrepancies in the results for the sand. It
346 would be interesting to perform complementary experiments with TDR arrays ([Sheng et al., 2017](#)) or
347 to assess the shape of SMC profiles when evaporation occurs. Our experiment also indicates that, at
348 least for some soils, it is necessary to improve the link between surface reflectance and SMC established
349 using Petri dishes.

350 Studying other soils covering the texture triangle, like in [Sadeghi et al. \(2017\)](#), would be worthwhile,
351 while keeping in mind that a large amount of matter ($\sim 350 \text{ cm}^3$) is needed to fill the aquarium. Several
352 spaceborne hyperspectral sensors are under development (e.g., EnMap, HypsIRI, Shalom) or already
353 operational (e.g., PRISMA) so that new remote sensing data will be soon available. The validation of
354 semi-empirical relationships or radiative transfer models for SMC retrieval using these data is an
355 important step before producing SMC maps routinely. In such a context, the comparison between
356 surface SMC and in-depth SMC is a key point regarding the link between hyperspectral imagery and in
357 situ measurements.

358

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