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# The Third Soil Moisture Active Passive Experiment

**A. Monerris** [a], **J.P. Walker** [a], **R. Panciera** [b], **T.J. Jackson** [c], **D. Gray** [d], **H. Yardley** [d], **and D. Ryu** [e]

[a] *Department of Civil Engineering, Monash University, Australia*
[b] *Cooperative Research Centre for Spatial Information (CRC-SI), University of Melbourne, Australia*
[c] *United States Department of Agriculture (USDA), USA*
[d] *Department of Electrical and Electronic Engineering, The University of Adelaide, Australia*
[e] *Department of Infrastructure Engineering, University of Melbourne, Australia*
*Email: sandra.monerris-belda@monash.edu*

**Abstract:** The National Aeronautics and Space Administration's (NASA) Soil Moisture Active Passive (SMAP) mission is scheduled for launch in 2014. This soil moisture dedicated mission will carry a combined L-band radar and radiometer system with the objective of mapping near surface soil moisture globally at an unprecedented spatial resolution. The scientific rationale for SMAP is an improved accuracy and spatial resolution of the soil moisture estimates through the unique combination of high resolution (3km) but noisy radar derived soil moisture information and the more accurate yet lower resolution (40km) radiometer derived soil moisture information, yielding a 10km active/passive soil moisture product. In order to achieve these objectives, algorithms need to be developed and tested using field data that simulate the future radar and radiometer SMAP data.

The Soil Moisture Active Passive Experiment (SMAPEx) contributes to the development and validation of such algorithms, by providing prototype SMAP observations collected with a unique active and passive airborne facility over a heavily monitored study area. SMAPEx comprised three campaigns across an approximately one year timeframe. The field work required by this project was undertaken in the Yanco intensive study area, located in the Murrumbidgee catchment in south-eastern Australia. The SMAP configuration is replicated by an airborne SMAP simulator using the Polarimetric L-band Multibeam Radiometer (PLMR; 1.41GHz) and the Polarimetric L-band Imaging Synthetic aperture radar (PLIS; 1.26GHz). Both instruments were mounted under the fuselage of the same aircraft to acquire concurrent observations of the same ground area. The Soil Moisture Active Passive Experiment (SMAPEx) comprises three campaigns across an approximately one year timeframe.

This paper outlines the airborne and ground sampling rationale of the recent third experiment (SMAPEx-3) and summarises the data collected. This campaign was conducted in the austral spring from 5 to 23 September, 2011. While the two previous 1-week experiments focused on the early stage of crops growth and on mature crops, respectively, the 3-weeks long SMAPEx-3 aimed to capture the crop growth process. These data will complete the seasonal SMAPEx data set and will be used for the validation of temporal change detection algorithms, since a wide range of soil moisture and crop conditions were observed during the campaign. Ground and airborne observations were acquired throughout crop growing season every 2-3 days, an interval similar to SMAP revisit time. A total of nine PLMR/PLIS flights over an area the size of the SMAP pixel were conducted during SMAPEx-3, underpinned by extensive ground soil moisture, vegetation, and soil roughness data. Radar only soil moisture retrieval over crops will also be attempted as an add-on of the third experiment. With this purpose, two airborne flights with LIDAR and hyperspectral sensors were conducted for validation of radar retrieval of vegetation parameters. Detailed vegetation structure ground samples will be used to forward modelling of L-band radar backscatter using a discrete scatterer approach.

***Keywords:*** Soil Moisture Active Passive Experiments (SMAPEx), soil moisture, vegetation, L-band, radiometer, radar.

## 1. INTRODUCTION

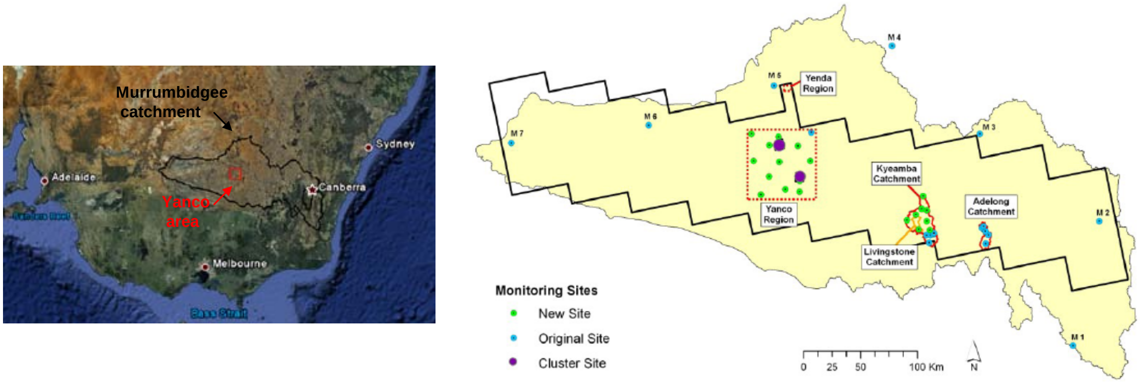
Knowledge of spatial and temporal variation in soil moisture at high resolution and with sufficient accuracy is critical for achieving sustainable land and water management. Such data are essential for efficient irrigation scheduling and cropping practices, accurate initialisation of climate prediction models, and setting the correct antecedent moisture conditions in flood forecasting models. The fundamental limitation is that spatial and temporal variation in soil moisture is not well known or easy to measure, particularly at high resolution over large areas. Remote sensing provides an ideal tool to map soil moisture globally and with high temporal frequency. Measurement of the microwave radiation has proved to be the most promising approach due to its all-weather capability and direct relationship with soil moisture through the soil dielectric constant. Whilst active (radar) microwave sensing at L-band (~1.4GHz) has shown some positive results, passive (radiometer) microwave measurements at L-band are least affected by land surface roughness and vegetation cover, which allows observations of the underlying layers. Consequently, the European Space Agency (ESA) launched the Soil Moisture and Ocean Salinity (SMOS) mission in November 2009, being the first-ever dedicated soil moisture mission based on L-band passive microwave radiometry (Kerr et al., 2010). However, space-borne L-band radiometric data provides low spatial resolution measurements, on the order of 40 km, which makes them appropriate for broad scale applications, but not useful for small scale applications such as on-farm water management, flood prediction, or meso-scale climate and weather prediction. To address the requirement for higher resolution soil moisture data, the National Aeronautics and Space Administration (NASA) proposed the Soil Moisture Active Passive (SMAP) mission. The basis for SMAP is that the high resolution (3 km) but noisy soil moisture data from the radar and the more accurate but low resolution (40 km) soil moisture data from the radiometer will be used synergistically to produce a high accuracy and improved spatial resolution (10 km) soil moisture product with high temporal frequency (Entekhabi et al., 2010).

Space missions for Earth observation require a huge amount of preparatory work to develop the science and technology. This is accomplished through airborne and/or ground-based field experiments. In preparation for the launch of SMAP, suitable algorithms and techniques need to be developed and validated to ensure that an accurate, high resolution soil moisture product from SMAP radar and radiometer data can be produced. The Soil Moisture Active Passive Experiment (SMAPEx) was specifically designed to address these scientific requirements (Panciera et al. 2010a, 2010b; Monerris et al., 2011). SMAPEx stems from the availability of an airborne remote sensing capability to undertake high resolution active and passive microwave remote sensing at L-band with resolution ratios, incidence angles and polarisations replicate to those expected from SMAP. The facility includes the Polarimetric L-band Multibeam Radiometer (PLMR) and the Polarimetric L-band Imaging Scatterometer (PLIS) which, when used together on the same aircraft allow simulation of the SMAP data with passive microwave footprints at 1km and active microwave footprints at better than 10m resolution when flown at a flying height of 3km.

SMAPEx comprises three campaigns across an approximately one year timeframe. The first campaign (SMAPEx-1) was conducted in the austral winter from 5-10 July, 2010. Weather conditions allowed observations of moderately wet winter in the range 0.15-0.25$m^3/m^3$ soil moisture. Vegetation contributions were minimal since the experiment was shortly after planting. The crop and grass biomass was within the range 0-1$kg/m^2$. The second campaign (SMAPEx-2) was conducted in the austral summer from 4-8 December, 2010. Intense rainfall lead to wet soil moisture conditions (0.25-0.33$m^3/m^3$), with surface water present at some locations. Due to warm moist conditions and delayed harvests, vegetation biomass was high, with crops at near-peak biomass (up to 4$kg/m^2$) and overgrown native pastures (up to 1.6$kg/m^2$). The third experiment (SMAPEx-3) was conducted in the austral spring, from 5-23 September, 2011. Moderate rainfall (35mm) was experienced in the study area the week before the experiment started, while some showers (up to 4mm) were registered during the first week. This lead to soil moisture values varying from 1-32$m^3/m^3$ in grazing areas and from 3-46$m^3/m^3$ in crops during the campaign. Vegetation contributions are expected to be low at the start and moderate at the end of the campaign, due to significant crop growth during the long-term SMAPEx-3. This paper provides a description of the recent SMAPEx-3 campaign and some preliminary results. An overview of SMAPEx-1 and SMAPEx-2 can be found in Gao et al. (2011) and Wu et al. (2011).

## 2. SMAPEX OVERVIEW AND RATIONALE

SMAPEx comprises three airborne campaigns in the Yanco study area located within the Murrumbidgee catchment (see Figure 1), in South-Eastern Australia. The three campaigns were scheduled to span across an approximately one year timeframe to encompass seasonal variation in soil moisture as well as vegetation growth stage, and to widen the range of soil wetness conditions encountered through capturing wetting or drying cycles associated to rainfall events. The third campaign (SMAPEx-3) took place in the austral spring




(a) (b)

**Figure 1.** (a) Location of the SMAPEx study area within the Murrumbidgee catchment (red square). (b) Overview of the Murrumbidgee River catchment, soil moisture monitoring sites, and the Yanco area.

from 5-23 September, 2011. The campaign commenced with moist soils and low vegetation biomass, leading to dry soils and high vegetation biomass towards the end of the 3-week long experiment. The scientific goals of the SMAPEx experiment are as follow:

- Test existing soil moisture retrieval algorithms for bare and vegetated surfaces from radar backscatter coefficients.
- Develop and test techniques to improve the soil moisture retrieval from radiometer brightness temperatures using information on the surface conditions (vegetation water content, VWC, and surface roughness) extracted from the radar backscatter coefficients.
- Develop and test techniques to downscale the coarse-resolution soil moisture retrieval from the radiometer brightness temperatures using the fine-resolution radar backscatter coefficients.

Apart from these, the specific goal of the third experiment was to acquire long-term series of data throughout the active part of the growing season, with the purpose of testing time-series retrieval algorithms. This paper describes the site and design of the SMAPEx-3 experiment, and provides a description of the data set.

## 3. THE YANCO STUDY AREA

The SMAPEx field experiments were undertaken in the Yanco intensive study area located in the Murrumbidgee Catchment, NSW, Australia (see Figure 1). This site had already been the focus of three other campaigns dedicated to algorithm development studies for the SMOS mission: the National Airborne Field Experiment 2006 (NAFE'06, www.nafe.unimelb.edu.au,) and the Australian Airborne cal/val Experiments for SMOS 1 and 2 (AACES, www.moisturemap.monash.edu.au/aaces). Therefore, Yanco constitutes a very suitable study site in terms of background knowledge, scientific requirements, and logistics. The SMAPEx study area is 34km × 38km in size, similar to the size of a SMAP pixel, and is located in the western plains of the Murrumbidgee catchment (see Figure 2). Soil types are predominantly clays, red brown earths, transitional red brown earth, sands over clay, and deep sands. Approximately one third of the study area is irrigated during the summer season, with summer crops being mainly corn, and soybeans, while winter crops include wheat, barley, oats, and canola.

The Murrumbidgee is a 100,000 km$^2$ catchment located in southeast of Australia (33-37S, 143-150E). There is significant spatial variability in climate, soils, vegetation, land use, and topography. The catchment is equipped with a wide-ranging soil moisture monitoring network (OzNet, www.oznet.org.au) which was established in 2001 and upgraded with 20 additional sites in 2003 and an additional 24 surface soil moisture probes in 2009 in the Yanco area (see Figure 3a-b). At present, the network consists in total of 38 continuously operating soil moisture profile stations distributed across the whole catchment, with three focus areas (Yanco, Kyeamba and Adelong) comprising about two-third of the existing monitoring sites (see Figure 1b). Each soil moisture site of the Murrumbidgee monitoring network measures the soil moisture at 0-8cm, 0-30cm, 30-60cm and 60-90cm with Campbell Scientific water content reflectometers. Soil moisture sites also monitor continuously soil temperature and precipitation.

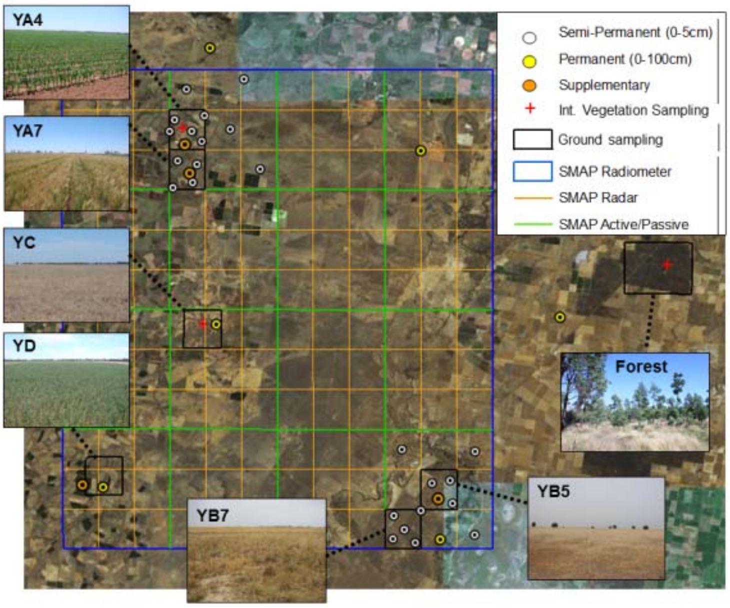



**Figure 2.** Overview of the Yanco site. The six ground sampling areas of SMAPEx (YA4, YA7, YC, YD, YB5, YB7) and the soil moisture monitoring stations are indicated.

## 4. AIRBORNE MEASUREMENTS

The primary aircraft instruments are the Polarimetric L-band Multibeam Radiometer (PLMR), used in across-track configuration (pushbroom), and the Polarimetric L-band Imaging Scatterometer (PLIS), with two antennas used to measure the surface backscatter to each side of the flight direction between 15° and 45°. Thermal and multispectral sensors are also installed in the aircraft. This infrastructure allows passive microwave (~1km), land surface skin temperature (~20m and 1km) and vegetation index (~1km) observations to be made across large areas. The aircraft can carry a typical science payload of up to 250kg with cruising speed of 150-270km/h (see Figure 3h). Aircraft instruments are installed in a fiberglass pod under the fuselage. Navigation is undertaken using a GPS driven 3-axis autopilot together with a cockpit computer display that shows aircraft position relative to planned flight lines using the OziExplorer software. The aircraft also has an OXTS (Oxford Technical Solutions) Inertial plus GPS system (two antennae on the fuselage) for position and attitude interpretation of the data. When combined with measurements from a base station, the system can give a positional accuracy of 2cm, roll and pitch accuracy of 0.03° and heading accuracy of 0.1°. A total of 9 regional flights are scheduled in SMAPEx-3 to replicate time-series data. Airbone data were collected three times per week, typically a day or two apart between flights. Airborne LIDAR and hyperspectral measurements were made twice using a second aircraft operated by Airborne Research Australia. The aircraft can carry a typical science payload of up to 120kg with cruising speed of 90-200km/h and endurance of 4-8hrs. Aircraft navigation for science is undertaken using a cockpit computer display only that shows aircraft position relative to planned flight lines using the OziExplorer software. The aircraft uses the same OXTS navigation system as the other aircraft (http://ara.es.flinders.edu.au/aircraft.htm).

The PLMR measures both vertical and horizontal (V and H) polarisations using a single receiver with polarisation switch at incidence angles ±7°, ±21.5° and ±38.5° in either across track or along track configurations. In the normal pushbroom configuration the 3dB beamwidth is 17° along track and 14° across track resulting in an overall 90° across track field of view. The instrument has a working frequency of 1.413GHz and bandwidth of 24MHz, with accuracy better than 1K for an integration time of 0.5s, and 1K repeatability over 4h. Hot and cold calibrations are performed before, during and after each flight. The before and after flight calibrations are achieved by removing PLMR from the aircraft and making brightness temperature measurements of a calibration target and the sky. The in-flight calibration is accomplished by measuring the brightness temperature of a water body (Lake Wyangan).

The PLIS measures the surface backscatters at HH, HV, and VV polarisations. It is composed of two send and receive 2×2 patch array antennas tilted 30° from the horizontal to either side of the aircraft to obtain pushbroom imagery over a cross track swath of ±45°. Both antennas are able to transmit and receive at V and


(a) (b) (c) (d)

(e) (f) (g)

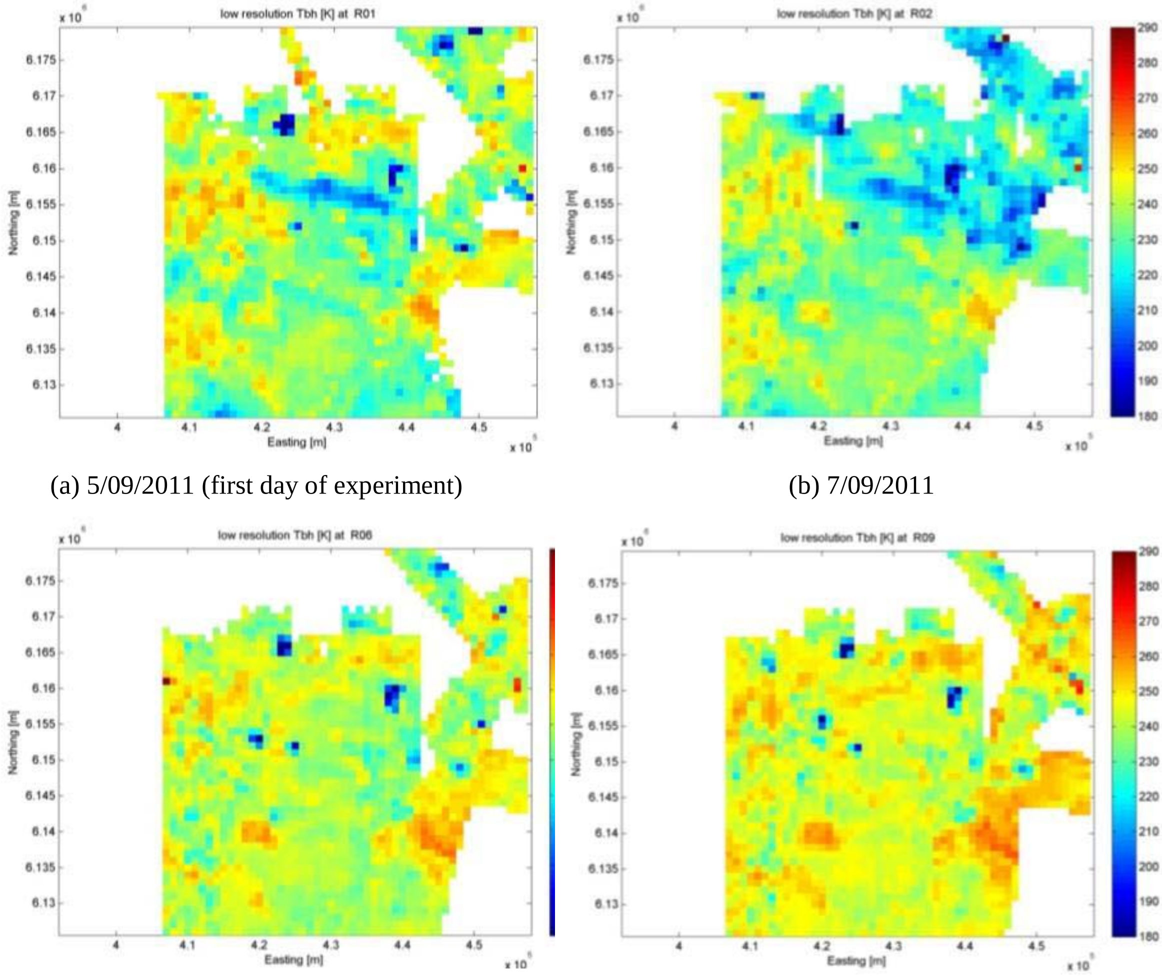
**Figure 3**. (a) Permanent, (b) semi-permanent, (c) supplementary stations; (d) HDAS for soil moisture sampling; (e)-(g) destructive, spectral and LAI vegetation sampling.

H polarisation. The antenna's two way 6-dB beamwidth is of 51°, and the antenna gain is 9dBi ±2dB. In the cross-track direction, the antenna gain is within 2.5dB of the maximum gain between 15° and 45°. PLIS has an output frequency of 1.26GHz, a bandwidth of 30MHz and a peak transmit power of 20W. The instrument can radiate with a pulse repetition frequency of up to 20 kHz with pulse width of 100ns to 10µs. The minimum detectable Normalized Radar Cross Section is of -45dB $m^2/m^2$. Calibration of PLIS is performed using three Polarimetric Active Radar Calibrators (PARCs) both at the beginning and at the end of the airborne monitoring to check for calibration drift during flight, together with six triangular trihedral passive radar calibrators (PRCs) distributed throughout the study area.

There are also six thermal infrared radiometers (TIR) with 8.0 to 14.0nm spectral range; the Everest Interscience 3800 with 15° field of view (FOV) and 0-5V output. These six TIRs are installed at the same incidence angles as PLMR so as to give coincident footprints with PLMR observations. Likewise, multispectral measurements are made using two arrays of 15° FOV Skye 4-channel sensors, each with 0-5V signal output. The available spectral bands are the following: MODIS band 1 (620–670nm), MODIS band 2 (841–876nm), MODIS band 3 (459–479nm), MODIS band 4 (545–565nm), MODIS band 6 (1628–1652nm), 2026–2036nm, MODIS band 7 (2105–2155nm), and 2206–2216nm.

## 5. GROUND SAMPLING

Ground monitoring for SMAPEx-3 was designed to validate the radiometer and radar airborne observations and hence provide supporting ground data for the prototype SMAP data. In addition to the network of continuous soil moisture monitoring stations (permanent and semi-permanent), six focus areas equivalent to six SMAP radar pixels (see black squares in Figure 2) were sampled. Within each area, ground sampling includes:




(a) 5/09/2011 (first day of experiment)

(b) 7/09/2011

(c) 18/09/2011

(d) 23/09/2011 (last day of experiment)

**Figure 4.** First low resolution brightness temperature images acquired with PLMR during SMAPEx-3.

- Supplementary monitoring stations (soil moisture and temperature, and leaf wetness);
- Intensive spatial sampling of the top 5cm soil moisture in a 250m grid;
- Intensive spatial vegetation sampling (destructive vegetation water content (VWC), spectral, and leaf area index (LAI)); and
- Intensive spatial monitoring of supporting data (land cover type, soil surface roughness, and soil gravimetric samples).

### 5.1. Supplementary monitoring stations

Permanent monitoring stations were supplemented by four identical temporary monitoring stations. These short-term monitoring stations are instrumented with a rain gauge, thermal infrared sensor (Apogee sensors), leaf wetness sensor (MEA LWS v1.1), two soil moisture sensors (Hydraprobes; 0-6cm and 23-29cm) and four soil temperature sensors (MEA6507A; 2.5, 5, 15 and 40cm depth) in order to provide time series data during the sampling period (see Figure 3c). Such measurements will be used for identifying the presence or absence of dew, and verifying the assumptions that (i) effective temperature has not changed significantly throughout the course of the aircraft measurements; (ii) vegetation and soil temperature are in near-equilibrium condition; and (iii) soil moisture has not changed significantly during ground sampling.

### 5.2. Spatial soil moisture and supporting data sampling

Intensive spatial ground sampling is focused on six 2.8km × 3.1km areas distributed across the SMAP radiometer pixel. Soil moisture was monitored in a 250m grid concurrently with aircraft overpasses using the Hydraprobe Data Acquisition System (HDAS) which consists of a pole in which a Hydraprobe and a rugged hand-held Getac PS236 have been installed (see Figure 3d). At each sampling location, information about land use, vegetation type, canopy height and presence of dew, and 0-5cm soil volumetric moisture samples are collected. Gravimetric soil moisture samples were made at isolated locations across the farm for calibration purposes. Surface roughness was characterised at 3 locations within each major land cover type in the focus areas. At each of the 3 locations, two 3m-long surface profiles were recorded using a pin profiler, one oriented parallel to the look direction of the PLIS radar (east-west) and one perpendicular to it (north-south). Roughness measurements were not made coincident with PLMR/PLIS overpasses.

### 5.3. Spatial vegetation monitoring

The VWC is crucial for modeling both the land surface emission and backscatter at L-band. The objective of the vegetation monitoring is therefore to characterise VWC across the study area. Multiple destructive biomass sampling was conducted for all dominant vegetation types at various stages of maturity and VWC, together with concurrent ground-based spectral and LAI observations. The purpose is developing interpolation relationships using aircraft and/or satellite spectral data. The instrumentation used for these purposes during SMAPEx-3 was the MultiSpectral Radiometer (MSR) developed by CROPSCAN and the LAI-2000. Information about vegetation type, canopy height, crop row spacing and direction are also recorded.

## 6. FIRST EXAMPLE OF DATA

Figure 4 shows some non-temperature-corrected, low-resolution brightness temperature (TB) images of the Yanco site acquired using PLMR during SMAPEx-3. As expected, a decrease in TB is observed in Figure 4b with respect to Figure 4a (first day of experiment), which is coincident with rainfalls in the area on Sept. 7. Soil drying from then on is visible in Figures 4c-d, where TB increases as soil moisture decreases.

## 7. SUMMARY

The Soil Moisture Active Passive Experiments (SMAPEx) constitute an excellent benchmark to develop and validate suitable algorithms to ensure that an accurate, high resolution soil moisture product from radar and radiometer data can be produced from SMAP data. The fieldwork was undertaken in the Yanco intensive study area, located in the Murrumbidgee catchment in south-eastern Australia. The SMAP configuration is replicated by an airborne system composed of the Polarimetric L-band Multibeam Radiometer (PLMR; 1.41GHz, H and V polarisations) and the Polarimetric L-band Imaging Synthetic aperture radar (PLIS; 1.26 GHz, VV, HH, and HV polarisations). Long-term series of data acquired during SMAPEx-3 throughout the active part of the growing season will help improving time-series retrieval algorithms and L-band radar and radiometer models.

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