The NAFE'05/CoSMOS Data Set: Toward SMOS Soil Moisture Retrieval, Downscaling, and Assimilation

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***Abstract*—The National Airborne Field Experiment 2005 (NAFE'05) and the Campaign for validating the Operation of Soil Moisture and Ocean Salinity (CoSMOS) were undertaken in November 2005 in the Goulburn River catchment, which is located in southeastern Australia. The objective of the joint campaign was to provide simulated Soil Moisture and Ocean Salinity (SMOS) observations using airborne L-band radiometers supported by soil moisture and other relevant ground data for the following: 1) the development of SMOS soil moisture retrieval algorithms; 2) developing approaches for downscaling the low-resolution data from SMOS; and 3) testing its assimilation into land surface models for root zone soil moisture retrieval. This paper describes the NAFE'05 and CoSMOS airborne data sets together with the ground data collected in support of both aircraft campaigns. The airborne L-band acquisitions included 40 km $\times$ 40 km coverage flights at 500-m and 1-km resolution for the simulation of a SMOS pixel, multiresolution flights with ground resolution ranging from 1 km to 62.5 m, multiangle observations, and specific flights that targeted the vegetation dew and sun glint effect on L-band soil moisture retrieval. The L-band data were accompanied by airborne thermal infrared and optical measurements. The ground data consisted of continuous soil moisture profile measurements at 18 monitoring sites throughout the 40 km $\times$ 40 km study area and extensive spatial near-surface soil moisture measurements concurrent with airborne monitoring. Additionally, data were collected on rock coverage and temperature, surface roughness, skin and soil temperatures, dew amount, and vegetation water content and biomass. These data are available at www.nafe.unimelb.edu.au.**

***Index Terms*—Microwave radiometry, National Airborne Field Experiment (NAFE), passive microwave, soil moisture, Soil Moisture and Ocean Salinity (SMOS).**

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I. Introduction

Knowledge of the soil moisture variability at a range of spatial and temporal scales is a constraining factor for the accurate simulation and prediction of environmental processes. Event-based hydrological modeling and flood forecasting, for example, require correct definition of the antecedent soil moisture condition [1]. At larger scales, the spatial distribution of soil wetness state is an important boundary condition to general circulation model predictions [2] both acting as a forcing and reacting to the forcing of meteorological phenomena [3]. The European Space Agency's (ESA's) Soil Moisture and Ocean Salinity (SMOS) mission will provide the first-ever dedicated global near-surface soil moisture data, providing the data needed to improve the environmental prediction. Moreover, the mission will carry the first-ever spaceborne 2-D interferometric radiometer operating at 1.4 GHz (L-band) with V- and H-polarized observations at a range of incidence angles [4], [5].

The utilization of this novel technique on a spaceborne platform poses several scientific questions yet to be answered. First, the implications of applying the L-band soil moisture retrieval algorithms developed from high-resolution or point measurements to large-scale heterogeneous scenes need to be assessed. Second, the theoretically demonstrated potential of the SMOS multiangle configuration for the retrieval of multiple land surface parameters needs verification and development. Third, methods need to be developed to overcome the mismatch between the spatial scale and the vertical depth at which the SMOS soil moisture information will be derived, and those at which this information is needed for many hydrological applications [6], [7]. Consequently, the utilization of data from the SMOS mission requires coordinated airborne and ground data collection campaigns to verify and refine the soil moisture retrieval algorithms. Moreover, the approaches for downscaling the low-resolution SMOS data and the assimilation techniques for root zone soil moisture retrieval need to be developed and verified to make optimal use of the SMOS data when they become available.

This paper describes the data collected during the joint National Airborne Field Experiment 2005 (NAFE'05) and the Campaign for validating the Operation of SMOS (CoSMOS), which were undertaken in the Goulburn River experimental catchment of southeastern Australia in November 2005. These coordinated airborne campaigns were specifically designed to address the key science questions outlined above.

To this end, relevant aircraft measurements were concurrently made with the ground observations of soil moisture and other related data. This data set is complementary with others around the world, including the series of the Southern Great Plains and the Soil Moisture Experiment campaigns in the U.S. (http://hydrolab.arsusda.gov) [8]–[10] and the European Surface Monitoring Of the Soil Reservoir Experiment (SMOSREX) [11], adding to the global soil moisture remote sensing database.

The airborne data were collected by two microwave radiometers, i.e., the Polarimetric L-band Multibeam Radiometer (PLMR) operated by the NAFE team and the EMIRAD L-band polarimetric radiometer [12] operated by the CoSMOS team. The NAFE ground sampling and aircraft monitoring activities were undertaken across a four-week period which started on October 31 and ended on November 25. The CoSMOS flights started on November 12th and ended on December 9th, and thus overlapped with NAFE operations for the first two weeks. Favorable meteorological conditions during the campaign period allowed the monitoring of a long drying period that followed a heavy rainfall on October 31 and November 1. Further scattered rainfall occurred toward the end of the campaign. The observed near-surface soil moisture contents ranged from full saturation to very dry conditions.

The analysis of this data set is currently underway at various institutions around the globe and includes the following: the investigation of the scaling properties of L-band soil moisture retrieval schemes for the operational downscaling of SMOS information to relevant hydrological and agricultural scales [13]; the testing of multisensor approaches (thermal, optical, and passive microwave) for soil moisture retrieval from the L-band [14]; and the analysis of the effect of sun glint on L-band observations and its effect on future SMOS soil moisture retrieval [15]. The data are being made available to interested parties to ensure that this extensive and unique data set is fully exploited in preparation for the SMOS data stream.

This paper is structured as follows. First, the general characteristics of the catchment and the study area are described. A summary of the data set is then presented starting with the ground data and ending with both NAFE and CoSMOS airborne data descriptions.

II. Study Site Description

The Goulburn River experimental catchment has been heavily instrumented for soil moisture, rainfall, and runoff since 2001, and a complete description of the catchment and associated long-term monitoring is given in [16]. Consequently, only the most pertinent catchment and long-term monitoring information is given here, with an emphasis on the study site and data collection descriptions that are specific to the campaigns described herein.

The Goulburn River is a tributary to the Hunter River in New South Wales, Australia. This 6540-km^2 experimental catchment extends from 31°46′S to 32°51′S and 149°40′E to 150°36′E with elevations ranging from 106 m in the floodplains to 1257 m in the northern and southern mountain ranges (Fig. 1). The terrain slope has a median of 8% and a maximum

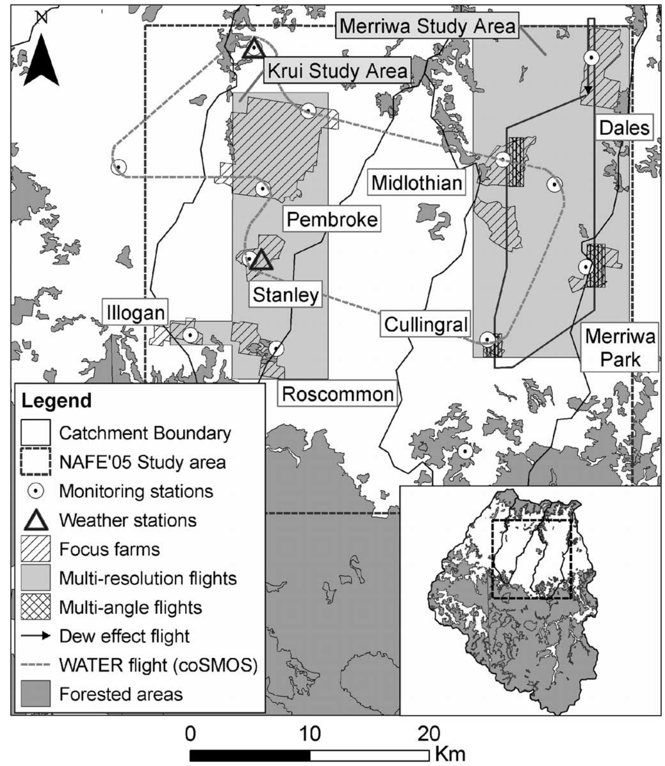

Fig. 1. Overview of the Goulburn catchment and permanent monitoring stations, the NAFE'05/CoSMOS study area, focus farms, campaign monitoring, and flight regions.

of 71%. The Goulburn River generally runs from west to east with tributaries in a predominantly north–south orientation. Much of the original vegetation has been cleared to the north of the Goulburn River, where grazing and cropping are the dominant land uses. In contrast, the southern portion of the catchment is largely uncleared (with extensive areas covered by forest). The soils in the area are primarily basalt-derived clays in the north, whereas the south is dominated by sandstone-derived sandy soils. The general climate within the region can be described as subhumid or temperate, with an average annual rainfall of approximately 650 mm and temperatures varying from a monthly mean maximum of 30 °C in summer to a monthly mean minimum of 2 °C in winter [16].

The aircraft and ground operations were concentrated on a 40 km × 40 km area in the northern part of the catchment (see Fig. 1). This area was chosen to represent a single SMOS pixel and was located in the mostly cleared northern part of the catchment for its moderate-to-low vegetation cover and concentration of soil moisture monitoring stations, which make it a candidate SMOS verification site. The area is characterized by a gently rolling landscape with mixed grazing and cropping land use.

There are two weather stations and 18 soil moisture profile stations within the area, with seven of the soil moisture stations concentrated in a 150-ha study catchment at the Stanley farm and the remainder uniformly distributed across the area. The area was logistically divided into two subareas, i.e., the Krui and Merriwa study areas, which are defined by the boundaries of two subcatchments formed by the Krui and Merriwa Rivers. Moreover, the farms that host eight of the soil moisture monitoring stations were selected as focus farms for ground

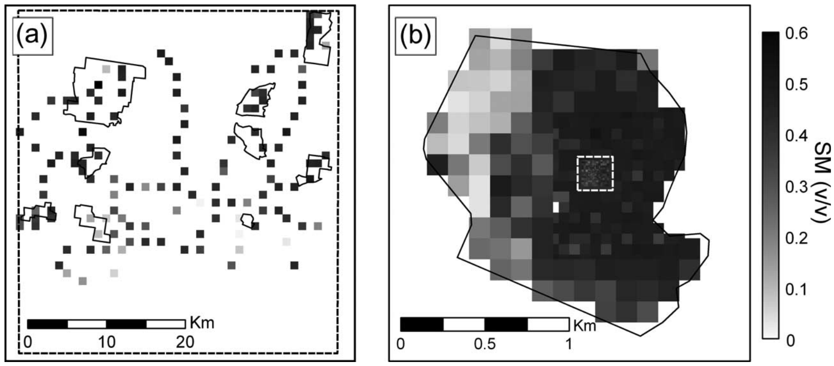

Fig. 2. Example of ground-sampled near-surface soil moisture maps (vol/vol). (a) Regional sampling on November 7, 2005. (b) Cullingral focus farm on November 4, 2005. The boundaries of the focus farms are in black solid lines. The high-resolution sampling area is outlined with white dashed lines, and the NAFE'05 study area is shown in black dashed lines.

sampling and high-resolution aircraft monitoring. These farms were selected as characteristic of the land cover and soil types present in the study area, and are indicated in Fig. 1. These farms range in size from 200 ha to nearly 7 km^2.

III. Ground Data

The Goulburn River experimental catchment has been instrumented with long-term soil moisture profile, rainfall, and runoff monitoring infrastructure since 2001 [16]. These sites were upgraded for near-surface soil moisture, temperature, and more extensive rainfall monitoring in preparation for the campaign. Moreover, eight of these monitoring sites were temporarily upgraded with thermal infrared (TIR) towers, near-surface soil temperature profiles, and leaf wetness sensors for the period of October 21 to November 27, 2005.

Spatial ground sampling was concentrated in the 40 km $\times$ 40 km region and eight focus farms, with the near-surface soil moisture data collected across the region and the farms at a range of spatial scales from 6.25 m to 2 km. Additionally, data were collected on land cover, rock coverage and temperature, surface roughness, skin and soil temperature, dew amount, and vegetation water content.

A. Near-Surface Soil Moisture Monitoring

The soil moisture within the top 5 cm of the soil profile was monitored coincident with each aircraft flight either across the entire area or across the focus farms, depending on the specific flight type. Additionally, measurements were continuously made at individual monitoring sites (see Section III-B).

On days when the entire 40 km $\times$ 40 km area was covered by aircraft measurements, the ground teams sampled the soil moisture on a grid of approximately 2 km, which was adapted to the network of accessible roads in the area. The measurements were made at a sufficient distance from the road in representative locations so as to avoid anomalous readings. Measurements of the top 5-cm soil moisture content were undertaken using an innovative Hydraprobe Data Acquisition System developed by The University of Melbourne that integrates a Global Positioning System and soil moisture sensor with a Geographic Information System [17]. A site-independent calibration of the Stevens Water Hydraprobe sensor used by this system was developed using gravimetric samples in the field and laboratory, and indicated that the data are accurate to within $\pm 3.5\%$ vol/vol [18]. An example of the resulting regional soil moisture map is shown in Fig. 2.

On all the other dates, the sampling was focused on two of the focus farms in the respective subcatchment being covered by multiresolution flights, with each farm mapped one or two times every week. The very high resolution sampling was concentrated on a 150 m $\times$ 150 m area, where the soil moisture was measured at 12.5-m (outer section) and 6.25-m (75-m inner square) spacing. The high-resolution areas on each farm were selected to capture the local spatial variability of the near-surface soil moisture associated with changes in vegetation cover, soil type, or microtopography. The area surrounding the very high resolution sampling areas was sampled at intermediate resolutions (125- to 250-m spacing). The remaining extent of the farm area was sampled at coarser resolution (500-m and/or 1-km spacing). The relative extent of the areas sampled at each resolution was optimized by maximizing the coverage at a finer scale while providing that the entire farm area was covered within a daily time window. This nested grid system provided very fine resolution soil moisture measurements for the validation of the high-resolution PLMR pixels, as well as characterizing the spatial variability of near-surface soil moisture from the very local scale, out to the paddock and farm scale.

B. Long-Term Soil Moisture Profile Stations

The continuous logging of near-surface and root zone soil moisture to 90-cm depth, together with the soil temperature, was ensured during the campaign by the existing Goulburn River experimental catchment monitoring network (see Fig. 1), which provides verification data for root zone soil moisture retrieval from the assimilation of remotely sensed data. A total of 26 monitoring sites were operating during the campaign. Of those, 18 were distributed across the study area at conditions chosen for typical vegetation, soil, and topographic aspect so that they represented catchment average soil moisture conditions. Note that seven of these sites were concentrated in a 150-ha study catchment at the Stanley farm, whereas the others were uniformly distributed across the area. Additionally, two automatic weather stations located in the area recorded meteorological data during the campaign [16].

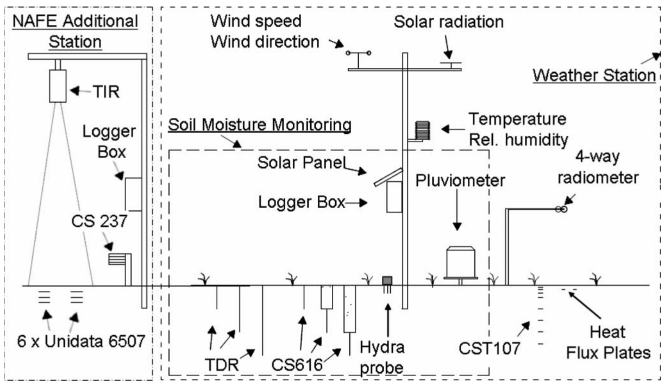

Fig. 3. Schematic of the Goulburn River experimental catchment weather and soil moisture stations. The large box includes the instrumentation typically installed at weather stations, whereas the smaller internal box shows the instruments typically installed at soil moisture monitoring sites. The additional NAFE instrumentation is shown in the left box.

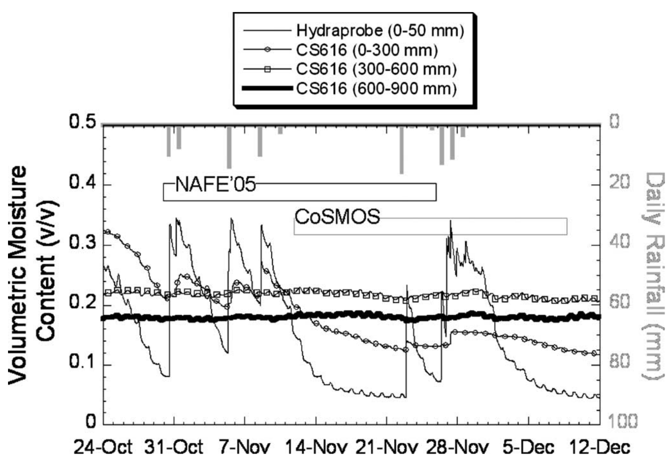

Fig. 4. Example of the soil moisture and rainfall time series data collected at the soil moisture monitoring sites during the campaign.

Each of the soil moisture sites had up to three vertically Scientific CS616 water content reflectometers over depths of 0–30, 30–60, and 60–90 cm, respectively, together with a Stevens Water Hydraprobe, which measures the soil temperature at 2.5 cm and the soil moisture in the 0- to 5-cm layer of soil. A typical installation for these sites is shown in Fig. 3, whereas Fig. 4 displays an example of the soil moisture and rainfall time series collected at one of the sites during the campaign period. The CS616 reflectometers were calibrated against both laboratory and field measurements [16].

C. Additional NAFE Monitoring Stations

Eight of the existing monitoring stations were supplemented with additional sensors for the duration of NAFE'05 (see Fig. 5). The primary purpose of this supplementary monitoring was to provide information on leaf wetness in response to dew and precipitation, and develop relationships between TIR observations and near-surface soil temperature. Consequently, the eight stations were all supplemented with soil temperature profile measurements with sensors at 1, 2.5, and 4 cm (Unidata 6507A/10 sensors), which are duplicated in most cases. At four of these stations, TIR radiometers (Ahlborn Thermalert TX or

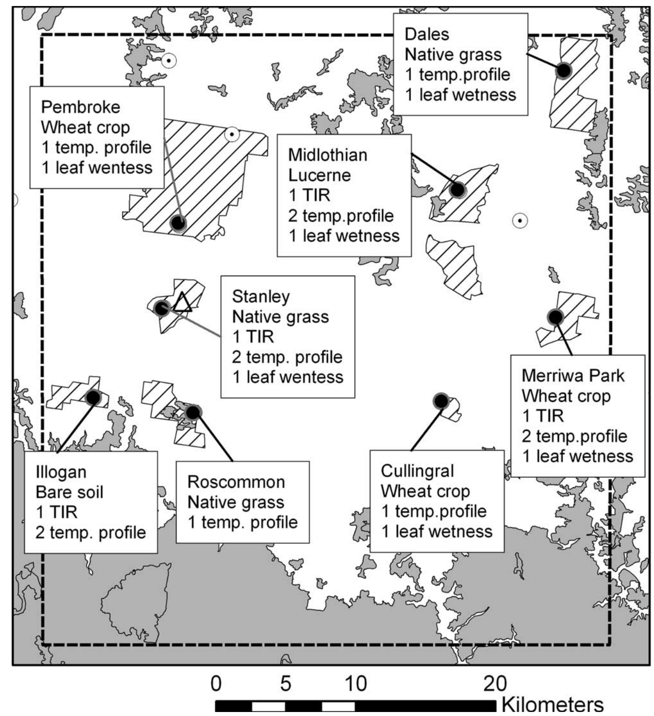

Fig. 5. Additional instrumentation installed during NAFE'05. The map shows the Goulburn River experimental catchment locations at which TIR, soil temperature sensors at 1, 2.5, and 4 cm (temperature profile), and leaf wetness sensors were temporarily installed during November 2005.

Everest Interscience Inc. Infrared Temp Transducers, Model 4000) were installed on 2-m-high towers (schematic of the setup is shown in Fig. 3). One of these was located at a bare soil site, whereas the other three were distributed among dominant vegetation types in the area (lucerne, wheat, and native grass). The leaf wetness sensors (Measurement Engineering Australia 2040) were installed at the four monitoring stations located at focus farms in the Merriwa area, where a dew-effect flight was undertaken, and at two focus farms in the Krui study area (Pembroke and Stanley) to check the spatial variability of dew across the entire area.

A specific station was set up for rock temperature monitoring to provide data for the analysis of the effect of surface rock on L-band passive microwave emission. The station had four Unidata 6507A/10 thermocouples embedded in the surface layer of the rock at different locations and was installed at the Stanley focus farm.

D. Vegetation Data

On each farm, the spatial variability of vegetation biomass and water content was characterized by collecting between four and sixteen 0.5 m $\times$ 0.5 m quadrant samples across the high-resolution soil moisture sampling area, supported by a minimum of five quadrant samples of the dominant vegetation types across the farm. This was undertaken once a week at fixed locations to monitor the temporal changes in vegetation biomass and water content. On all the other days, the vegetation water content samples were collected from two corners of the high-resolution areas as a check on the temporal changes of the farm vegetation water content. On the two dates when an early morning dew flight was undertaken, two further vegetation water content samples were collected for the farm reference vegetation at first light to estimate the amount of vegetation dew by comparison with the samples taken later during the day.

The vegetation reflectance and the leaf area index were also measured for the high-resolution areas of each focus farm with the objective to develop relationships for vegetation water content and biomass estimation. An Exotech Inc. LAI-2000 and an Exotech Inc. Hand Held Radiometer 100BX were used to measure, respectively, the leaf area index and the normalized difference vegetation index at 50-m spacing within the 150 m $\times$ 150 m high-resolution soil moisture sampling areas. This was done at least once during the campaign at each farm.

E. Other Data

The supporting ground data that were collected during the campaign included volumetric soil samples, surface roughness measurements, vegetation type and land use classification, surface rock cover, and leaf wetness estimates. The top 5-cm volumetric samples of soil were collected across the study area for both soil textural analysis and calibration of the Stevens Water Hydraprobe. A total of 20 samples were collected at each focus farm, which were aimed at characterizing the different soil types and wetness conditions across the farm. On two dates, further soil samples were collected across the entire study area, which makes a total of 120 samples. The soils were oven dried for 24 h to calculate the thermogravimetric water content.

The surface roughness was estimated once during the campaign at a minimum of four locations on each focus farm to capture the different roughness characteristics according to land cover type. Two 1-m-long roughness profiles were recorded for each measurement location, i.e., one north–south and one east–west oriented.

The dominant vegetation type, land use, and surface rock cover were recorded at each soil moisture sampling location. This was undertaken for both regional and farm sampling grids. The presence of dew was visually estimated and daily recorded as no dew, moderately wet, or very wet to support the leaf wetness measurement made at the monitoring stations.

IV. Aircraft Data

The NAFE and CoSMOS aircraft flights were carried out by the following two concurrently operating aircraft: 1) a Diamond ECO-Dimona from Airborne Research Australia national facility, which is equipped with the NAFE team-operated PLMR (an imaging instrument) developed by ProSensing, and 2) an Aero-Commander 500S Shrike also operated by Airborne Research Australia, which carries the CoSMOS team-operated EMIRAD (a line instrument) developed by the Technical University of Denmark.

A. Instrument Characteristics

The two microwave radiometers operate at the same frequency. The main difference between the two is in the aperture, which results in different ground spatial resolutions, swath coverage, and measurement characteristics. The key characteristics of these two radiometers are compared in Table I.

TABLE I
PLMR AND EMIRAD CHARACTERISTICS

CHARACTERISTIC	PLMR	EMIRAD
Frequency/ bandwidth	1.413GHz/ 24MHz	1.413GHz/ 22MHz
Polarization	V and H	V, H 3'rd, 4'th Stokes (Fully polarimetric)
Spatial resolution/ swath	50m/ 300m (150m flying height)	100m/ 100m (150m flying height)
Incidence angles	+ / - [7º, 21.5º, 38.5º] across track (rotatable by 90 º for along-track operation)	0º - 40º along track
Antenna beamwidth	13 º (inn. beams) -16.5º (out. beams) across track 17 º along track	37.6 º (nadir)/ 30.6 º (aft looking)

1) PLMR

The PLMR is a dual-polarized L-band radiometer. The small instrument size and weight enabled the use of a light aircraft as the observing platform, which makes it a suitable low-cost and flexible tool for environmental monitoring. PLMR uses six pushbroom patch array receivers with incidence angles of $\pm 7^\circ$, $\pm 21.5^\circ$, and $\pm 38.5^\circ$, and measures both V- and H-polarized brightness temperatures (TB) for each beam using a polarization switch. The six beams can be oriented either across track (image) or along track (multiangle). The change between these configurations was achieved in NAFE'05 by manually rotating the instrument through 90° prior to multi-angle flights so that the beams pointed forward/backward with respect to the aircraft axis. The reduced antenna beamwidth coupled with an ability to fly low and slow allowed unprecedented ground spatial resolution with a footprint size of approximately 50 m for a 150-m flying height (3-dB beamwidth). The aircraft payload also included an FLIR S60 thermal imager with 80° field-of-view lens carried on all flights and a Canon EOS 1Ds 11-megapixel digital camera specifically installed for a single aerial photography flight.

The calibration of the radiometer was performed daily during the campaign against warm (ambient blackbody) and cold (sky) observations before and after every flight. Apart from the sun, galactic background noise was not considered during sky observations as it is generally estimated to be less than 1 K even when exactly pointing to the galactic plane. The effect of this assumption on the calibration accuracy in the range considered is estimated to be less than one-tenth of a kelvin, which is negligible in the context of soil moisture remote sensing. However, extreme care was taken to avoid sun or other terrestrial interferences in any of the six beams.

In-flight calibration checks included flights over Lake Glenbawn and sky-looks with the outermost beams through a series of steep turns. Lake Glenbawn is located 100 km east of the Goulburn catchment and was instrumented for the monitoring of surface water temperature and salinity. Weekly water temperature and salinity transects over the lake were also undertaken to check for spatial gradients. Beam-specific calibration coefficients were derived and applied for each day of the campaign by averaging the preflight and postflight coefficients for each beam. The calibration drift during the flight (i.e., the difference between the coefficients calculated for preflight and postflight calibration) was not found to be serious given the accuracy needed for soil moisture. The calibrated radiometer data have been geolocated by taking into consideration the aircraft position, pitch, roll, and yaw information recorded for each measurement, with the beam centers projected onto a 250-m digital elevation model of the study area. The effective footprint size and the ground incidence angle have also been calculated by taking into consideration the aircraft attitude and terrain slope.

The accuracy in the full calibration range (10–300 K) was found to be better than 1.1 K for H polarization, whereas at V polarization it varied from 1.5 K for inner beams to 2.5 K for outer beams. When considering the measurement range over land during the campaign (150–300 K), the accuracy was better than 0.7 K at H polarization and 2 K for V polarization.

2) EMIRAD

The EMIRAD is a fully polarimetric L-band radiometer system that employs two antennas installed in the aircraft such that the ground is viewed at along-track incidence angles of 0° (nadir) and 40° in the aft direction. The antennas are Potter horns with no sidelobes. The two horns were designed such that they have approximately the same footprint on the ground. A nadir-looking Heiltronics KT15 TIR radiometer was also operated on all flights. This infrared (IR) instrument has a 4° beamwidth, which thus produces a footprint that is almost ten times smaller than the L-band sensor.

The EMIRAD was calibrated in the laboratory at a normal ambient temperature before the CoSMOS campaign. This basic calibration uses a hot load and a liquid-nitrogen-cooled load. The liquid nitrogen calibration was repeated on several occasions during the campaign. An excellent instrument stability was achieved (better than 1 K). During flights, the internal calibration was achieved by means of an internal load and a noise diode. During normal operating conditions, the radiometer was temperature stabilized to 40 °C with a stability to better than 0.02° for a 15° change in ambient temperature. This, together with the internal calibration, ensured very good stability of the measured TB. Due to the higher than expected ambient operating temperatures, the laboratory calibration was extended after the campaign to temperatures of 48 °C. The calibration accuracy was confirmed by flights over Lake Glenbawn. Comparing the EMIRAD readings over the lake with the simulated water TB indicated an accuracy of better that 1 K for V and H polarization at both incidence angles. The EMIRAD L-band data have also been geolocated by taking into consideration the aircraft position and the attitude information obtained during flights. More details about EMIRAD data calibration and validation are given in [15].

The lake calibration flights were normally independently performed by the CoSMOS and NAFE teams. However, a number of coordinated cross-calibration flights were performed for comparison between the two sensors. The comparison between the EMIRAD and PLMR observations for flights over Lake Glenbawn revealed an up to 2 K average difference for H polarization and up to 6 K average difference for V polarization [15]. It should be noted however that the flight timing differed by up to 45 min and that the EMIRAD footprint size was approximately 120 m while that for the PLMR was down to 30 m.

B. NAFE Flights

A total of approximately 100 h of NAFE mission flights were conducted during the campaign. All flight lines were north–south oriented to be parallel to the geomorphology of the area and to avoid the strong variation in terrain elevation, as well as direct sun glint in the outermost beams. Moreover, this orientation is similar to the planned SMOS flight path. Full coverage of the same ground area was guaranteed by allowing a full PLMR pixel overlap between adjacent flight lines for the median ground altitude of the area. The following five flight types were conducted: 1) regional; 2) multiresolution; 3) multiangle; 4) dew; and 5) aerial photography. These are summarized in Table II.

The regional flights were performed over the entire 40 km × 40 km study area. These flights were scheduled according to the local overpasses of the Aqua platform to provide supporting fine-scale passive microwave data for comparison with this C-band AMSR-E mission. The flight altitude was 3000 m Above Ground Level (AGL) with the data generally acquired between 6:00 A.M. and 10:00 A.M. These flights were undertaken every Monday and provided four maps of L-band microwave emissions at a nominal ground resolution of 1 km. Due to the rough terrain, the effective pixel size varied between approximately 860 and 1070 m, which resulted from flying at a constant altitude above the median elevation of the study area. An example of the regional maps acquired (H polarization) is shown in Fig. 6.

The two multiresolution flight types were specifically designed to address the L-band scaling issues by acquiring observations of the same area at various resolutions. This required the subsequent mapping of the same focus area with different altitude flights. Due to the long flight time required, the entire study area could not be covered during these flights; therefore, two focus areas of approximately 10 km × 30 km were selected for the alternate multiresolution flights. These areas were the Merriwa and Krui study areas (see Fig. 1). The multiresolution flights were undertaken four times per week, alternating between the two focus areas. For each flight, the focus area was covered at four different altitudes in descending order (3000, 1500, ∼750, and ∼200 m AGL), which results in L-band maps at approximately 1000-, 500-, 250-, and 62.5-m spatial resolutions, and TIR maps at approximately

TABLE II
NAFE/CoSMOS FLIGHT DESCRIPTION

	Flight type	Altitude (AGL)	Configuration	Ground resolution	Schedule
NAFE	Regional: SMOS pixel simulation	3000m	PLMR (push-broom)	1000m	Once a week (Mon) (with AMSR-E overpasses)
			Thermal Infrared	20m	
	Multi-resolution: SMOS downscaling	3000m 1500m 750m 200m	PLMR (push-broom)	1000/500/250/62.5m	Four times a week (Tue, Wed, Thurs and Fri)
			Thermal Infrared	20/10/5/1.25m	
	Multi-angle: SMOS algorithm development	750m	PLMR (multi-angle)	250m	Once a week (Wed) + 2 unscheduled (November 11^{th} and 18^{th})
			Thermal Infrared	5m	
	Dew: effect of vegetation dew on L-band retrieval	1500m	PLMR (push-broom)	500m	Twice (November 4^{th} and 25^{th})
			Thermal Infrared	10m	
	Aerial photography	1500m	Optical camera	0.5m	Once (November 2^{nd})
CoSMOS	ASSI: Assimilation of root zone soil moisture	550m	EMIRAD (line)	375m	Three times a week*
			Thermal Infrared	50m	
	SCAL: Scaling issues	1900m	EMIRAD (line)	1300m	Once** (November 21^{st}, 23^{rd}, and December 9^{th})
			Thermal Infrared	160m	
	GLINT: Sun Glint and Topography	500m	EMIRAD (line)	340m	Once (November 15^{th})
			Thermal Infrared	35m	
	WATER: Effect of vegetation water content and dew	500m	EMIRAD (line)	340m	Twice (November 14^{th} and 22^{nd})
			Thermal Infrared	35m	

* Only 2 times on week 2 and week 3 and only 1 time on week 4, due to technical problems

* * Completed in 3 days

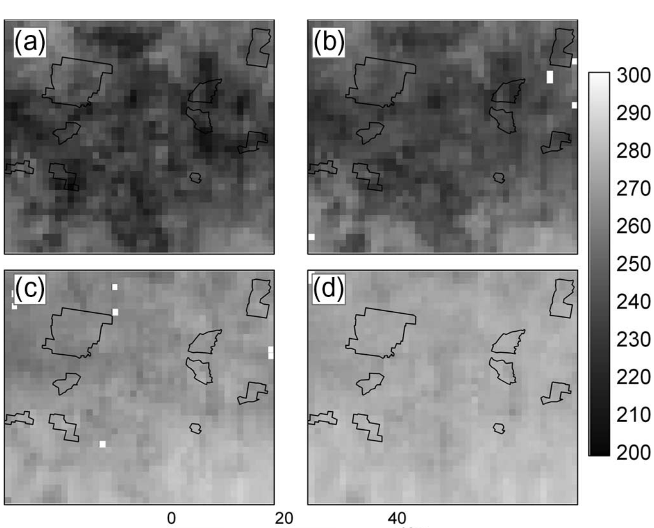

Fig. 6. PLMR L-band H-polarized passive microwave observations (K) for the four regional mapping flights. (a) October 31. (b) November 7. (c) November 14. (d) November 21. The boundaries of the eight focus farms for ground sampling are displayed for reference.

20-, 10-, 5-, and 1.25-m resolution. The flights generally started at 6:00 A.M. and finished at 11:00 A.M. To avoid gaps in the data due to the reduction in pixel size in the northern part of the study area caused by terrain elevation, which is particularly important for the two lower flights, the flights were conducted with a variable flight altitude for the various farms. An example of multiresolution mapping over the Krui subarea is shown in Fig. 7. An important issue to be considered in comparing these acquisitions at different resolutions is the temporal change in the ground land surface conditions throughout the flight. The ground monitoring of these variables and the comparison of overlapping pixels from adjacent flight lines can be used to correct for this effect.

A total of six multiangle flights were performed for the specific purpose of answering the science question of multi-incidence angle retrieval of soil moisture. During these flights, the PLMR was mounted on the aircraft in the along-track configuration, which yields three forward and three backward looking beams. These flights were flown at a nominal altitude of 750 m (AGL), which results in a pixel size of approximately 250 m, over three focus farms in the Merriwa study area, i.e., Merriwa Park, Cullingral, and Midlothian (see Fig. 1). The farms were selected to have reasonably flat areas of uniform

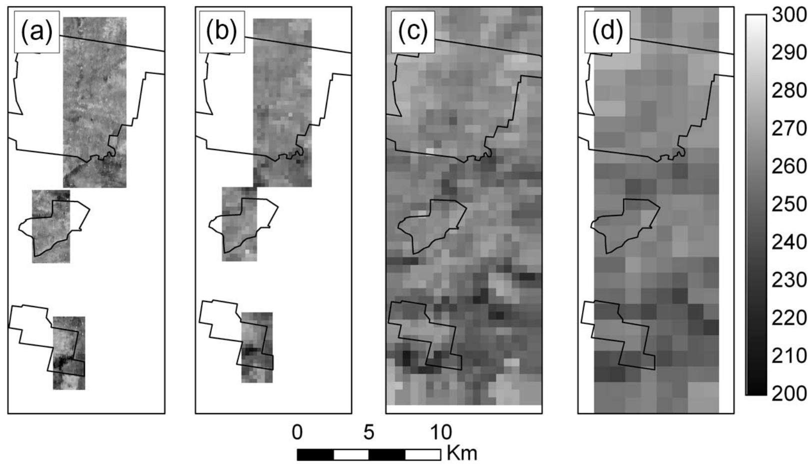

Fig. 7. Example of the multiresolution PLMR L-band H-polarized passive microwave observations (K) in the Krui area for November 1, 2005. Nominal resolutions displayed are (a) 62.5 m, (b) 250 m, (c) 500 m, and (d) 1000 m. The boundaries of the focus farms for ground sampling are displayed for reference.

vegetation cover to avoid topographic effects on the microwave signal and facilitate the multiparameter retrieval of both soil moisture and vegetation water content. The multiangle flights took place in the early afternoon immediately following the multiresolution flights, i.e., approximately between 12:00 P.M. and 2:00 P.M. To increase the range of incidence angles at which observations were taken, each multiangle flight was followed by a "dive" flight that involves successive steep ascents and descents in altitude.

To assess the effect of vegetation dew on the soil microwave signal, two early morning flights were undertaken in the 30 km $\times$ 20 km focus area of the Merriwa catchment, on a day when regular multiresolution flights were scheduled for the same area later during the day. This was done to allow the comparison of the microwave signal before and after the drying off of the dew. The dew effect flights consisted of a circuit through the four soil moisture and dew monitoring stations (see Fig. 1). One single loop was flown at first light. The nominal altitude for this flight was 1500 m AGL, which results in a ground resolution of approximately between 400 and 550 m.

C. CoSMOS Flights

A total of 13 EMIRAD flights were performed over the Goulburn catchment with approximately 30 h of CoSMOS mission flight time [15]. The following four flight types were conducted: 1) assimilation; 2) scaling and heterogeneity; 3) sun glint and topography; and 4) vegetation water content and dew. All flights started at approximately 6:00 A.M. to match the land surface conditions corresponding to the SMOS local overpass time of 6:00 A.M./6:00 P.M. The characteristics of these flights are summarized in Table II.

The greatest amount of flight time was dedicated to the assimilation flights. The aim of these flights was to provide L-band observations at sites where the soil moisture profile was continuously monitored to develop root zone soil moisture retrieval from the assimilation of SMOS soil moisture observations. The flight altitude was 550 m AGL with a nominal ground resolution of 375 m, and the route included the eight Goulburn River experimental catchment monitoring sites of the NAFE focus farms, as shown in Fig. 1. These flights were performed three times during the first week but were then reduced to two times a week in the following two weeks and only one flight was performed in the fourth week.

The scaling and subpixel heterogeneity issues were addressed through a single 1300-m nominal resolution (1900 m AGL altitude) mapping flight across a 50 km $\times$ 50 km area centered on the NAFE'05 study area. Because of EMIRAD being a line instrument, the full coverage of the area took three days to be completed, i.e., November 21, 23 and December 9.

The sun glint and topography effect flights were performed once during the campaign over the Roscommon farm (including grass and forest). The sun is a strong L-band source, and the effect of its reflection on the land surfaces to the surface TB has hardly been studied. These flights consisted of successive ascents and descents in altitude first toward and then away from the sun position, which was normally performed between 7 A.M. and 10 A.M. local time, which at the time of the experiment corresponded to solar zenith angles of approximately 45° and higher. The range of observation angles achieved through the dives overlapped the solar zenith angle, which therefore makes it possible to investigate the contribution of the sun's L-band reflection to the surface TB in the direction of the highest reflection.

The effect of vegetation water content and dew was investigated by two flights during the campaign which overpassed two of the focus farms (Illogan and Roscommon) where the concurrent ground sampling of vegetation water content and dew was undertaken. The altitude chosen for these flights was 500 m, with a 340-m nominal ground resolution. The circuit over the two focus farms was repeated from sunrise from midmorning to observe the effect of dew dry off.

V. DATA AVAILABILITY

The NAFE'05/CoSMOS data described in this paper are available at http://www.nafe.unimelb.edu.au. The web site provides all the information needed for the interpretation of these data, along with general information on the Goulburn catchment, photographs of the landscape, sampling methods, and a full experiment plan. Due acknowledgment in any publication or presentation arising from the use of these data is required.

VI. Summary

This paper has presented the airborne and ground data set of the joint NAFE'05/CoSMOS campaign. This extensive field campaign was the result of the collaborative efforts of a number of Australian, European, and American institutions, including The University of Melbourne, University of Newcastle, National Aeronautics and Space Administration (NASA), ESA, Airborne Research Australia, the Free University of Amsterdam, Centre d'Etudes Spatiales de la Biosphère (CESBIO), the University of Valencia, and the Technical University of Denmark.

The airborne observations included concurrent L-band acquisitions at different incidence angles (0°–40°) and ground resolution (1 km to 62.5 m) over a moderately vegetated 40 km × 40 km area, which corresponds to an SMOS pixel. The airborne data were supported by ground observations of near-surface soil moisture spatial variability and soil moisture profile temporal change. The data set has a great potential for addressing the important science question related to the SMOS mission, including the following: 1) development of the SMOS retrieval algorithms; 2) developing approaches for downscaling the low-resolution data from SMOS; and 3) testing its assimilation into land surface models for root zone soil moisture retrieval. Furthermore, the very high resolution L-band data (down to 62.5 m) collected for the first time during NAFE'05 will allow the development of the PLMR radiometer soil moisture product for future aircraft-based SMOS calibration studies. An important potential use of these data is to also test the suitability of the soil moisture monitoring network operating in the Goulburn catchment area for SMOS validation.

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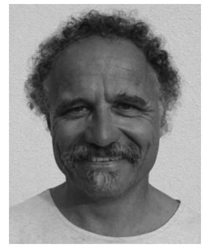

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