The CoSMOS L-band experiment in Southeast Australia

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Abstract— **The CoSMOS (Campaign for validating the Operation of the Soil Moisture and Ocean Salinity mission) campaign was conducted during November of 2005 in the Goulburn River Catchment, in SE Australia. The main objective of CoSMOS was to obtain a series of L-band measurements from the air in order to validate the L-band emission model that will be used by the SMOS (Soil Moisture and Ocean Salinity) ground segment processor. In addition, the campaign was designed to investigate open questions including the sun-glint effect over land, the application of polarimetric measurements over land, and to clarify the importance of dew and interception for soil moisture retrievals. This paper summarises the campaign activities, and presents progress on the analysis of the CoSMOS data set.**

Keywords-soil moisture; L-band; SMOS; passive microwaves

I. INTRODUCTION

The CoSMOS campaign was a joint collaboration between the European Space Agency (ESA), the University of Melbourne, the University of Newcastle, and several European centres working on the preparation of the SMOS mission. During CoSMOS, the EMIRAD [1] L-band radiometer was flown over crop fields and prairies for four weeks. The first two weeks overlapped with the National Airborne Field Experiment (NAFE'05, [2]), that also generated a rich L-band data set supported by intensive field measurements.

The objectives of CoSMOS were three-fold. First, CoSMOS allowed mapping an area of approximately 35 km x 50 km at L-band. In this way, the microwave model L-MEB [3] used by SMOS, currently implemented from high-resolution field experiments, will be tested at a lower resolution over crops and prairies. Second, CoSMOS included specific flights that will be used to address open questions for SMOS such as the effect of sun-glint over land and the quality of soil moisture retrievals with wet vegetation. Finally, the CoSMOS data set will be used to aggregate brightness temperatures nearly at the scale of a SMOS pixel, and to validate the soil moisture retrievals performed by the SMOS Level 2 algorithm with ground-based measurements of soil moisture.

This paper describes the CoSMOS experiment and presents examples of the ongoing studies using the CoSMOS data set.

II. THE GOULBURN RIVER CATCHMENT

The area of study is within the Goulburn river catchment (31.77 S to 32.85 S, 149.67 E to 150.60 E) in New South Wales (Australia). This semi-arid catchment was selected by the NAFE team for the 2005 campaign given the moderate vegetation cover, and the presence of a soil moisture measurement network from the SASMAS project (Scaling and Assimilation of Soil Moisture and Stream flow) within GOREX (GOulburn River Experiment). The area covered by the catchment is approximately 6540 km^2, with a central plateau (300-450 m above sea level) dedicated to crop growth and grazing, delimited by mountainous regions to the north and south. The Goulburn River catchment has two sub-catchments monitored since September 2001 through the SASMAS project: the Krui river sub-catchment on the northwest side (562 km^2), and the Merriwa river sub-catchment on the northeast side (651 km^2). Both the CoSMOS and NAFE campaigns focused on four farms located within the Krui sub-catchment, and four farms located within the Merriwa sub-catchment. Table 1 summarises the characteristics of each farm. Calibration operations during CoSMOS took place at the Glenbawn Lake, located to the east of the Goulburn River catchment.

III. L-BAND MEASUREMENTS

The EMIRAD radiometer was mounted onboard an Aero Commander 500S Shrike aircraft, operated by Airborne Research Australia. EMIRAD is a fully polarimetric radiometer developed by TUD (Technical University of Denmark) operating in the 1400 – 1427 MHz band. Two Potter antennas were used for CoSMOS: one facing nadir with 37.6° full aperture at half-power ; the other was placed towards the rear of the aircraft at 40° zenith angle with 30.6° full aperture at half-power. In addition, the aircraft was equipped with an inertial navigation unit combined with a GPS receiver for aircraft attitude and position measurements. At the typical flight altitude (550 m above the surface), the antennas produced a footprint size of about 375 m at nadir, and 541 m x 197 m off-nadir.

EMIRAD flights were performed on 13 days between the 13th of November and the 9th of December of 2005. Four different types of flights were conducted (Table 2): i) 'REGULAR' flights were conducted soon after dawn, for about an hour, and provided a single pass over each of the eight focus farms, ii) 'WATER' flights were performed on one day from early to mid-morning in order to analyse changes in the brightness temperatures linked to changes in the internal vegetation water content and dew, iii) one 'GLINT' flight was dedicated to study the effect of reflected L-band radiation from the Sun on the surface, iv) 'SCALING' flights provided measurements from a higher altitude to analyse the importance of the change of scale. Finally, calibration flights over water were usually performed before and after the main operations over land. Thermal infrared measurements at nadir were obtained concurrently to L-band data. For that purpose a Heimann KT15 sensor was used (full beam-width is 4 degrees).

Another L-band radiometer, the Polarimetric L-band Multi-beam radiometer (PLMR), was used by the NAFE team to acquire L-band measurements at about +/-7º, +/-21.5º and +/-38º. Most flights used an across-track configuration. PLMR flights started two weeks before CoSMOS, and overlapped with CoSMOS for two weeks. PLMR data were obtained between 200 m to 3 km above ground level. The antenna used by PLMR has a narrower aperture (13º to 16.5º full beam-width at half-power) than the EMIRAD horns, however the observation of the same targets still allows intercomparison between two L-band sensors over water and land.

A correction of both aircraft pitch, roll, and heading was applied to EMIRAD and PLMR data to locate the centre of the footprints on the ground. The geolocation also included a topographic correction. However, given the large antenna aperture, especially for EMIRAD, it might be necessary to improve the footprint location by accounting for the antenna pattern, in particular when modelling the brightness temperature of mixed pixels.

IV. FIELD MEASUREMENTS

Field measurements included intensive sampling of the surface soil moisture (0-6 cm), as well as other ancillary measurements commonly performed in passive microwave experiments (vegetation biomass, soil roughness, soil texture, etc). Details are available in [4]. Soil moisture was measured by means of capacitance probes (HydraProbe) at different resolutions, from very high (6.25 m) covering a small area, to about 1 km covering the entire farm, and 2 km covering the entire region. This type of sampling was conducted once a week at each farm during the NAFE campaign period. Once a week the soil moisture sampling was dedicated to cover most of the Goulburn River catchment at a resolution of 2 km or lower. In addition to the intensive field campaign, soil moisture data at different depths (from the surface down to 90 cm) were obtained through the SASMAS stations distributed across the catchment: 4 stations within the Merriwa sub-catchment, and 11 within the Krui sub-catchment, with 7 of them located at a 1 km^2 micro-catchment. These stations also provided temperature readings between 0 and 30 cm deep. Some of these stations were implemented for NAFE with additional soil temperature sensors, a leaf wetness sensor (MEA2040), and a thermal infrared sensor.

V. FIRST RESULTS

Some of the ongoing studies based on the large data set acquired during CoSMOS are presented together with first results.

A. Sensitivity of EMIRAD to the surface characteristics

This section illustrates EMIRAD brightness temperatures (TB) measured near nadir and at about 40 degree zenith angle over different land surfaces: native grass over dry and wet soil (Stanley farm, on Nov 17 and Nov 27 respectively), crops over dry and wet soil (Cullingral farm, on Nov 17 and Nov 27), and native grass over dry and wet soil but in a more rocky area (Dales farm, on Nov 17 and Nov 29). Those three farms were selected as there is a small mixture of land uses within each farm. Table 3 summarises EMIRAD measurements at H and V polarisations, together with the third (T3) and forth (T4) Stokes parameters, which are related to the linear polarisation of the electric field at ± 45 degrees, and to the circular polarisation respectively. References to fully polarimetric data over land are almost non-existent in the literature as T3 and T4 should be zero for randomly oriented objects. Moreover, fully polarimetric models of the surface emission are not available. However, it is unclear whether land features do in fact introduce a polarimetric signature, for example through the orientation of crops or stems, and whether that signature could assist in the retrieval of soil moisture.

Table 1. Characteristics of each farm. B*: black basaltic clays, R*: red basaltic clays [4]

Sub-catch.	Farm	Area (ha)	Dominant land use	Topography	Soil
Krui	Pembroke (PEM)	6400	grazing,wheat	hilly,gently rolling	B*
Krui	Stanley (STA)	720	grazing	hilly	B* R*
Krui	Illogan (ILLO)	560	barley,oats, wheat,grazing	flat,gently rolling	B*
Krui	Roscommon (ROS)	940	grazing, forest	flat,gently rolling	R*, sandy
Merriwa	Dales (DAL)	1500	grazing	Sloping/creek	B*
Merriwa	Midlothian (MID)	2000	grazing,lucerne wheat,sorghum	flat/hilly	B*
Merriwa	Merriwa Park (MER)	750	grazing,wheat	gently sloping	B*
Merriwa	Cullingral (CULL)	220	wheat,lucerne	flat	B*

Table 2. Summary of EMIRAD flights and approximate altitude above ground level (AGL) . 'R' (REGULAR, 550 m AGL), 'W' (WATER, 500 m AGL), 'S' (SCALING, 1900 m AGL), 'G' (GLINT,diving flight). Farm abbreviations are given in Table 1.

DoE	KRUI FARMS				MERRIWA FARMS			
	PEM	STA	ILLO	ROS	DAL	MID	MER	CULL
13/11								
14/11	-	-	R,W	R,W	-	-	-	-
15/11	R	R	R	R,G	R	R	R	R
17/11	R	R	R	R	R	R	R	R
21/11	-	-	-	-	S	S	-	S
22/11	-	-	-	-	-	W	-	W
23/11	S	R, S	R	R	R	R	R	R
27/11	R	R	R	R	5 km	R	R	R
28/11								
29/11	R	R	R	R	R	R	R	R
03/12	R	R	R	R	R	R	R	R
06/12	-	-	-	-	-	-	-	-
08/12	-	-	-	-	-	-	-	-
09/12	S	S			1 km			

Table 3. Summary of EMIRAD measurements over land. Each cell shows mean brightness temperatures in K, and standard deviation in brackets. Grass 1 is for the Stanley site, Grass 2 is for the Dales site. TIR is the thermal infrared temperature in deg Celsius at nadir. Top) Nadir horn, Bottom) Off-nadir horn.

Surface	TVnadir	THnadir	T3nadir	T4nadir	TIR
Crop,dry soil	265 (2)	265 (1)	-0.19 (0.7)	1.2 (0.5)	35.8 (0.4)
Crop, wet soil	235 (4)	235 (4)	-0.06 (0.6)	-0.17 (0.4)	42.8 (0.2)
Grass 1, dry soil	264 (2)	264 (3)	-0.16 (2.2)	1.4 (2.1)	33.7 (0.5)
Grass 1, wet soil	229 (10)	230 (10)	0.29 (1.2)	-0.15 (0.5)	42.4 (0.4)
Grass 2, dry soil	260 (1)	260 (1)	-0.4 (0.8)	0.9 (0.6)	36.0 (0.6)
Grass 2, wet soil	229 (6)	230 (6)	0.4 (1.6)	-0.4 (0.7)	36.8 (0.2)

Surface	TV-40	TH-40	T3-40	T4-40	TIR
Crop, dry soil	272 (1)	262 (2)	-1.22 (1.1)	1.4 (0.6)	35.8 (0.4)
Crop, wet soil	253 (3)	230 (3)	-3.3 (3)	1.6 (0.8)	42.8 (0.2)
Grass 1, dry soil	270 (2)	263 (5)	-0.4 (3.2)	1.22 (2)	33.7 (0.5)
Grass 1, wet soil	246 (10)	230 (16)	-1.8 (3.9)	0.90 (1)	42.4 (0.4)
Grass 2, dry soil	266 (1)	259 (2)	-1.7 (2.4)	1.3 (0.7)	36.0 (0.6)
Grass 2, wet soil	237 (6)	220 (7)	-5.5 (2.3)	2.3 (0.7)	36.8 (0.2)

EMIRAD brightness temperatures at H and V polarisation show small differences near nadir as expected, and they are sensitive to soil moisture in all cases. At nadir, the dynamic range between dry and wet conditions was about 35 K for grass, and 30 K for crops. In all cases soils are clays. Note that the thermal infrared temperature was higher on the wetter day, showing that for similar surface temperatures the contrast at L-band would be even higher. Off-nadir, the difference between brightness temperatures at H and V polarisations increased for wet soils as expected. Such difference was around 16-23 K on the selected wet days, and about half of that on dry days. Note also that the deviation from the mean brightness temperature measured within each farm increased for wet soil, this is, brightness temperatures were more homogenous in dry conditions.

Concerning T3 and T4, no clear correlation with the surface characteristics can be highlighted at this time. T3 values at nadir were usually between 2 K and -2 K, although some peaks, which could be due to RFI, were also detected. This is under investigation. T4 though decreased about 1 K from dry to wet soil at nadir. We are investigating this feature that was observed in the eight farms when comparing dry to wet soils, as this is unexpected from a physical point of view.

B. *Comparison between PLMR and EMIRAD sensors*

During CoSMOS it was possible to obtain measurements of the same targets from two microwave radiometers. This section shows measurements of the two sensors over Glenbawn Lake, used as the calibration site in both cases. The two instruments though differ in the type of radiometer and antennas used, and also on the footprint size. Because the PLMR aperture is about half that of EMIRAD, and flights were performed at a lower altitude, the PLMR footprint at nadir over water was about 30 m in diameter, while the EMIRAD footprint was about 120 m.

A comparison between the two instruments is shown in Figure 1. The top of that figure shows measurements with a local zenith angle at the surface level between nadir and +/-5 degrees (nadir horn), and between nadir and +/-8 degrees for PLMR (+/-7-degree beams). The bottom row of the figure includes measurements between +/-35 and +/-40 degrees off-nadir. Just for comparison, the simulated brightness temperature values at those zenith angles are plotted too (crosses in Figure 1). These reference values have been calculated using the L-MEB model [3] over water, and measurements of the water temperature and salinity. For the EMIRAD cases shown in Figure 1, the RMSE between modelled and measured brightness temperatures was 2.4 K [std=0.6 K] at H polarisation, and 1.5 [std=0.9 K] at V polarisation for the nadir horn. Off-nadir, the RMSE was 3 K [std=0.9 K] at H, and 2.1 K [std=1.4 K] at V polarisation. EMIRAD data showed TBs through the H polarisation channel that were higher than expected. This was observed both when comparing H and V measurements near nadir, as well as by comparing to model simulations. Such difference is currently being investigated, as it has also been detected over land.

PLMR measurements plotted near nadir showed slightly higher values at V than at H polarisation (2.5 K on average at most) that can be partially attributed to the incidence angle variations (less than 1 K).

Differences in the mean TB values between the two sensors, averaged for each flight, were under 2 K at both polarisations for the off-nadir antenna shown in Figure 1. The largest difference was observed near nadir, where PLMR measurements were higher than EMIRAD measurements (up to 2 K on average at H polarisation, and up to 6 K at V polarisation). These are preliminary results, and we expect that further processing is likely to lead to a better agreement between the two L-band sensors.

C. *Sun-glint effects over land*

The CoSMOS flight plan included a set of flights aimed at studying the effect of sun-glint on L-band measurements over land. The sun is a very strong L-band source, and its reflection on land surfaces is likely to add to the overall surface brightness temperature, particularly at H polarisation, and for wet soils. However this effect has hardly been studied.

EMIRAD flights normally took place between 7-10 a.m. local time, which at the time of the experiment corresponded to solar zenith angles of approximately 45 degrees and higher. Six diving flights performed in the southern part of the Roscommon farm (including grass and forest) allowed observations of the surface at a range of angles. The diving flights were performed by performing successive ascents and descents in altitude. The antenna pointing direction changed with changes in the aircraft pitch, and so did the observation angle as a result. This is illustrated in Figure 2, where the different zenith angles of observation caused by the aircraft diving are shown together with the solar zenith angle. The overlap between the solar zenith angle and the measured

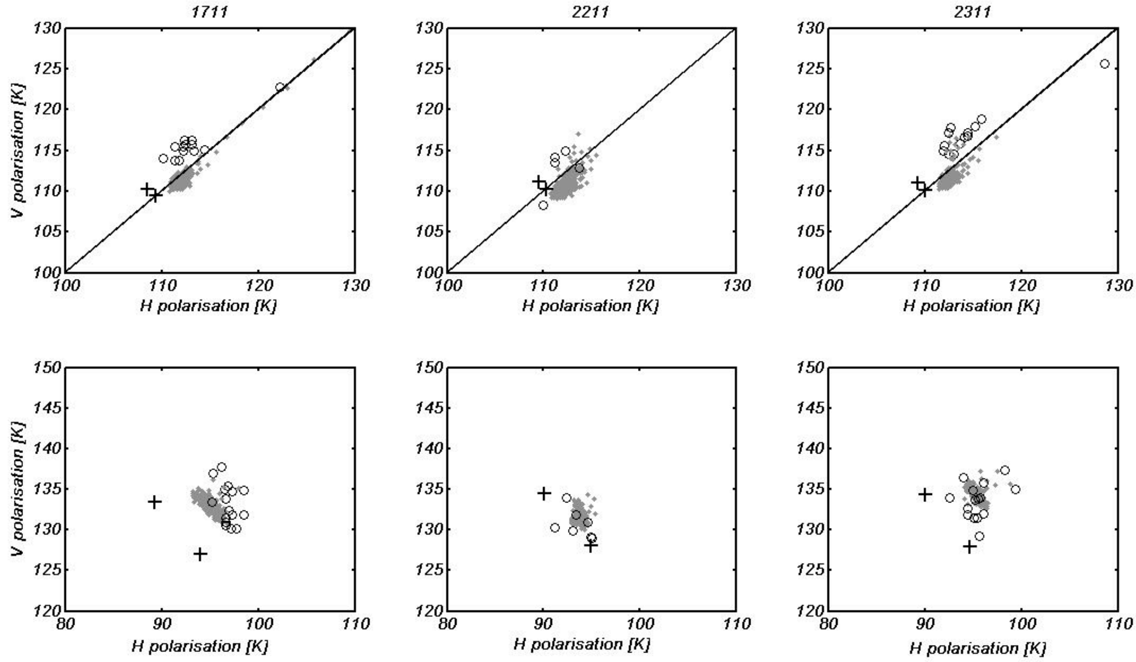

Figure 1. Comparison between PLMR (circles) and EMIRAD (dots) over water. Top) EMIRAD nadir horn and PLMR +/-7 deg beams, Bottom) EMIRAD off-nadir horn, PLMR +/-38 deg beams. The two crosses (+) represent simulated brightness temperatures at 0 and 8 degrees (top figures), and at 35 and 40 degrees (bottom figures) for each calibration flight.

zenith angles at L-band was achieved mainly from the off-nadir horn, for zenith angles around 45 degrees. A priori we have not observed a large contribution of the sun's L-band reflection in the direction of highest reflection. However, further modelling work is underway to determine the magnitude of the sun-glint contribution when integrated over the whole antenna pattern. For that purpose, the sun-glint effect on PLMR flights, where the antenna aperture is smaller, are being investigated.

VI. CONCLUSION

The CoSMOS field campaign was an opportunity to obtain L-band data from an aircraft simultaneously to the NAFE L-band campaign in the Goulburn River catchment. As a result the two campaigns have generated a 'multi-configuration', 'multi-scale', and 'multi-surface' six-week data set of great interest for the forthcoming SMOS mission. This data set is currently under analysis, with the objective of testing the SMOS retrieval algorithm with real data, as well as addressing relevant issues for microwave applications at L-band which are not fully understood, such as the contribution of sun-glint to the overall surface brightness temperature, or the use of fully polarimetric radiometers for soil moisture estimation. This paper has summarised the campaign activities, and illustrated some of the ongoing studies.

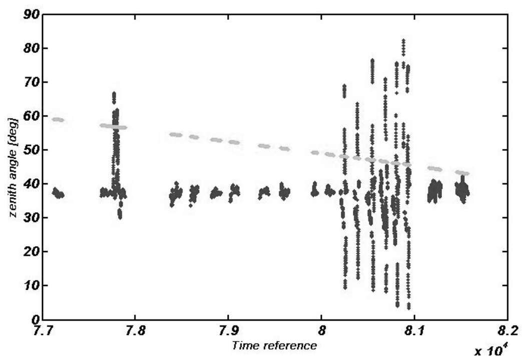

Figure 2. Illustration of the sun-glint diving flights. The EMIRAD true zenith angle at the surface (dark grey) is shown together the solar zenith angle (light grey). Time reference in seconds.

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