Measuring Ocean Salinity with ESA's SMOS Mission

– Advancing the Science

M. Berger[1], A. Camps[2], J. Font[3], Y. Kerr[4], J. Miller[5], J. Johannessen[6], J. Boutin[7], M.R. Drinkwater[1], N. Skou[8], N. Floury[1], M. Rast[1], H. Rebhan[1] & E. Attema[1]

[1] ESA Directorate of Earth Observation, ESTEC, Noordwijk, The Netherlands
[2] Polytechnic University of Catalonia, Barcelona, Spain
[3] Institut de Ciències del Mar CMIMA-CSIC, Barcelona, Spain
[4] CESBIO, Toulouse, France
[5] Naval Research Laboratory, Stennis Space Center, USA
[6] Nansen Environmental & Remote Sensing Center (NERSC), Bergen, Norway
[7] Université Paris Pierre et Marie Curie, Paris, France
[8] Technical University of Denmark, Lyngby, Denmark

The Soil Moisture and Ocean Salinity (SMOS) mission is ESA's second Earth Explorer 'opportunity mission', scheduled for launch in early 2006. Selected for an extended feasibility (Phase-A) study in 1999, which was completed in December 2001, SMOS is currently in the design and development phase (Phase-B).

SMOS will exploit an innovative instrument designed as a two-dimensional interferometer for acquiring brightness temperatures at L-band (1.4 GHz) to retrieve soil moisture and ocean salinity. Both are key variables used in weather, climate and extreme-event forecasting. As a secondary objective, data acquired by SMOS over ice/snow regions may be used to characterise the ice and snow layers and thus complement other satellite observations to advance the science of the cryosphere*.

Introduction

Ocean-salinity observations from space have been identified as a high priority in the Integrated Global Observing Strategy-Partnership (IGOS-P) Ocean Theme Team Report (Lindstrom et al., 2001). The goal in observing ocean salinity is derived from the Global Ocean Data Assimilation Experiment (GODAE) requirements, which include global observation of ocean salinity with an accuracy of 0.1 practical salinity units (1 psu = 1 g salt in 1 kg of seawater), every 10 days at 200 km spatial resolution. This poses a challenge not only in the instrument's design, but also for the retrieval technique, including measurement corrections.

This article outlines ESA's science activities dedicated to advancing our knowledge of the ocean-salinity signal and it's dependence on sea-state condition, in order to develop and enhance retrieval techniques for the SMOS mission.

The ocean-salinity objectives

Knowledge of the distribution of salt in the global ocean and its annual and inter-annual variability are crucial in understanding the role of the ocean in the climate system. It is well known that ocean currents and air-sea heat fluxes are regulating our climate. The Gulf Stream, for instance, transports warm surface water from the Caribbean to Europe, which is the reason for the moderately mild winters in central and northern Europe. As the Gulf Stream flows north and northeastward, the surface water cools and becomes denser. Moreover, evaporation will simultaneously increase the surface salinity and hence further increase the density. As a result, the ocean surface layer will gradually reach a density such that stable stratification with the water below can no longer be maintained. It will then trigger convective overturning and form deep water. The corresponding overall basin-scale, three-dimensional oceanic flow is commonly known as the 'thermohaline circulation'. Sea-surface salinity is therefore one of the key variables for monitoring and modelling this global oceanic circulation pattern, which in itself is an important indicator for climate change.

Ocean-surface salinity is closely correlated with estimates of net Evaporation minus Precipitation (E-P). The E-P balance is difficult to measure accurately over the ocean by

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* See also http://www.esa.int/livingplanet

conventional means, and so satellite-based maps of ocean salinity would provide a tool to constrain (E-P) estimations at global scale. It would provide insights into the phenomena driving the thermohaline circulation and allow better estimation of the latent heat flux. More accurate knowledge of the (E-P) balance would also improve the characterisation of the stratification of the surface layer of the ocean, and thereby improve estimates of the mixed-layer depth variation and its impact on the intensity of the surface currents.

The scientific objectives for observing ocean salinity with the SMOS mission are to:
– *Improve seasonal to inter-annual (ENSO) climate predictions:* Effective use of ocean-salinity data to initialise and improve the coupled climate-forecast models, and to study and model the role of fresh-water flux in the formation and maintenance of barrier-layer and mixed-layer heat budgets in the tropics.
– *Improve the estimates of the ocean rainfall and thus the global hydrologic budgets:* The 'ocean rain gauge' concept shows considerable promise in reducing uncertainties in the surface freshwater flux on climate time scales, given ocean-salinity observations, surface velocities and adequate mixed-layer modelling.
– *Monitor large-scale salinity events:* This may include ice melt, major river run-off events, or monsoons. In particular, tracking inter-annual ocean-salinity variations in the Nordic Seas is vital to long-time-scale climate prediction and modelling.
– *Improve monitoring of sea-surface salinity variability:* This is needed in order to better understand and characterise the distribution of bio-geochemical parameters in the ocean's surface.

The Global Ocean Data Assimilation Experiment (GODAE), a pilot experiment set up by the Ocean Observations Panel for Climate, which aims to demonstrate the feasibility and practicality of real-time global ocean modelling and assimilation systems, proposed an accuracy requirement for satellite salinity for global ocean-circulation studies of 0.1 psu for averages over 10-day time intervals in 200 km x 200 km boxes.

Considering the exploratory nature of SMOS, the GODAE open-ocean requirement represents a valid scientific goal, but is nevertheless a serious technical challenge. The image reconstruction errors, their correlation characteristics, the calibration stability, and the uncertainty related to the contribution of the surface characteristics of the signal may only allow salinity to be retrieved with lower accuracy, particularly at higher latitudes. This has to be carefully addressed with the continued development of the SMOS demonstrator and numerical simulator to analyse the SMOS ocean-retrieval accuracy. It should furthermore be emphasised that lower temporal resolution, e.g. monthly aggregated products, would be sufficient for many climate studies, and may offer improved accuracy. Lower salinity accuracy, and thus higher spatial or temporal resolution (typically 0.5 psu, 50 km, 3 days) would provide the means to monitor moving salinity fronts in various regions.

Signal sensitivity and perturbing factors

The dielectric constant for seawater is influenced, among other variables, by salinity. It is therefore possible to estimate sea-surface salinity from passive microwave observations, as long as other variables influencing the brightness-temperature (T_b) signal can be accounted for. These include Sea-Surface Temperature (SST), surface roughness, foam coverage, sun glint, rainfall, ionospheric effects and galactic/cosmic background radiation. Estimates have previously been made of the uncertainties associated with some of these perturbing factors.

The sensitivity of the brightness temperature to ocean salinity is a maximum at low microwave frequencies and the best conditions for salinity retrieval are found at L-band (1.4 GHz). However, it must be stressed that even at this frequency the sensitivity of the brightness temperature to salinity is low (at nadir 0.75 K per psu for an SST of 30ºC, decreasing to 0.5 K per psu at 20ºC, and 0.25 K per psu at 0ºC), placing demanding requirements on the performance of the instrument (Figs. 1a,b). Additional information for constraining the retrievals is provided by the multi-angular viewing and the polarisation.

Since the radiometric sensitivity is low, it is clear that ocean salinity cannot be estimated with the required accuracy from a single pass. However, if the errors contributing to the uncertainty in brightness temperature are random, the necessary accuracy can be obtained by aggregating the individual SMOS measurements in both space and time. In the following, this combination of measurements made at various incidence angles and various times will be referred as an 'averaging procedure', although the way in which the measurements will be combined needs to be thoroughly studied. The averaging procedure calls for excellent stability (0.02 K/day) from the radiometer.

The ocean-salinity retrieval from L-band radiometric measurements implies the use of ancillary data sources, for wind and SST in particular. As the ancillary data will not be recorded simultaneously with SMOS, the averaging procedure will allow use of data acquired (or analysed) at different times within the average window. The effects of the spatial and temporal variabilities of these data on the ocean-salinity retrieval have to be analysed.

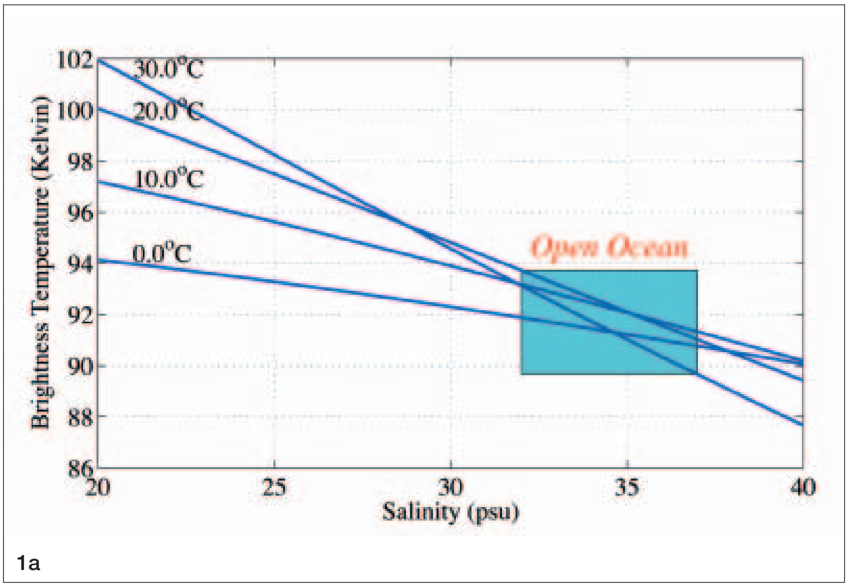

Figure 1a. Variation in brightness temperature due to sea-surface salinity at L-band as a function of SST for nadir observations (from Lagerloef et al., 1995)

Scientific support studies

The analysis, enhancement and validation of models accounting for signal-perturbing effects such as wind (azimuthal dependence, roughness and foam), sea-surface temperatures, rain, Faraday rotation and the timeliness of collocated observations, needed to be addressed by scientific support studies. In addition, appropriate campaigns had to be organised and conducted to provide suitable data. Once elaborated, the enhanced retrieval schemes, together with the system error budget, a vicarious calibration scheme, and a final-product definition will provide insight into the expected usefulness of SMOS data for the ocean-salinity objectives via dedicated impact-assessment studies. The following paragraphs briefly outline the activities initiated by ESA during the Phase-A study and the preliminary results therefrom.

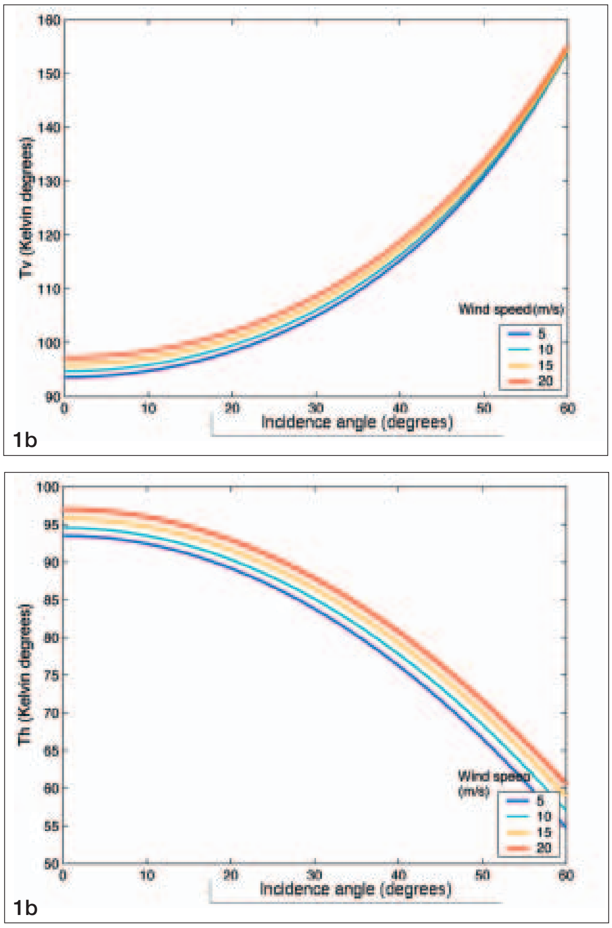

Figure 1b. T_v and T_h as a function of incidence angle for various wind speeds (5, 10, 15 and 20m/s) as simulated by a two-scale model at 35 psu and 15°C, without foam effect (from Dinnat et al., 2002; Yueh, 1997)

The Ocean Salinity Requirement Study

A study addressing the requirements for a future space-borne mission to observe sea-surface salinity was kicked-off in September 2000 and was completed in April 2002. The study was managed by NERSC of Norway as prime contractor, and involved a consortium of 10 institutes within Europe. The main objectives were a scientific-observation requirements analysis and impact assessment for ocean-atmosphere and thermohaline circulation models using different salinity accuracies, and more specifically to:

- examine and quantify the effects of surface-roughness changes, presence of foam, precipitation, and diurnal sea surface temperature variations on sea surface emissivity and derive the resulting Sea-Surface Salinity (SSS) retrieval accuracy over incidence angles ranging from nadir to 50°
- examine and quantify the impact of the SSS measurements with the above accuracy on ocean (and coupled ocean-atmosphere) modelling for different regions characterised by cold surface water, fresh-water input from rivers, melting sea ice and ice sheets, and evaporation minus precipitation, as well as in regions with limited temporal and spatial changes in surface salinity.

State-of-the art ocean-circulation models were used to provide a first qualitative assessment of the expected salinity signal. Three different models were applied to characterise typical SSS variations for different oceanic regions:

- the Océan PArallélisé (OPA) global ocean model, from LODYC, Paris, focusing on the Indian Ocean

- the CLIPPER model developed for the Atlantic Ocean, and
- the Miami Isopycnic Coordinate Ocean Model (MICOM) model, adopted by the NERSC team focussing on the Northeast Atlantic and Nordic Seas.

Using these model simulations, a variety of dynamic features like boundary currents (Gulf Stream, Benguela Current), tropical regions with high fresh-water exchange due to precipitation and river discharges were analysed. Characteristic salinity patterns and their temporal and spatial variations have been derived. The typical example shown in Figures 2 and 3 is for the Atlantic Ocean.

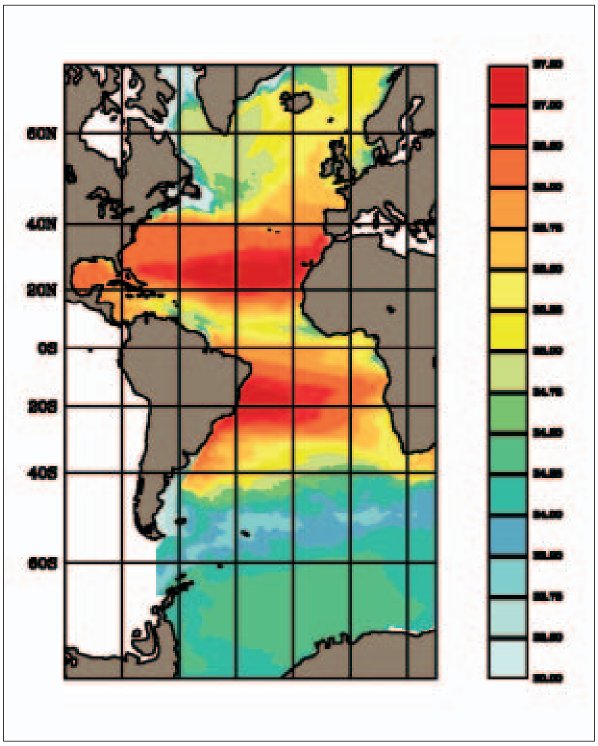

Figure 2. Simulated Sea Surface Salinity (SSS) distribution in the Atlantic using the Clipper model (mean SSS over the period 1997-1999). The model has not been adjusted for climatological values, resulting in higher SSS values for certain regions. However, a non-adjusted simulation provides a more realistic distribution of SSS variations

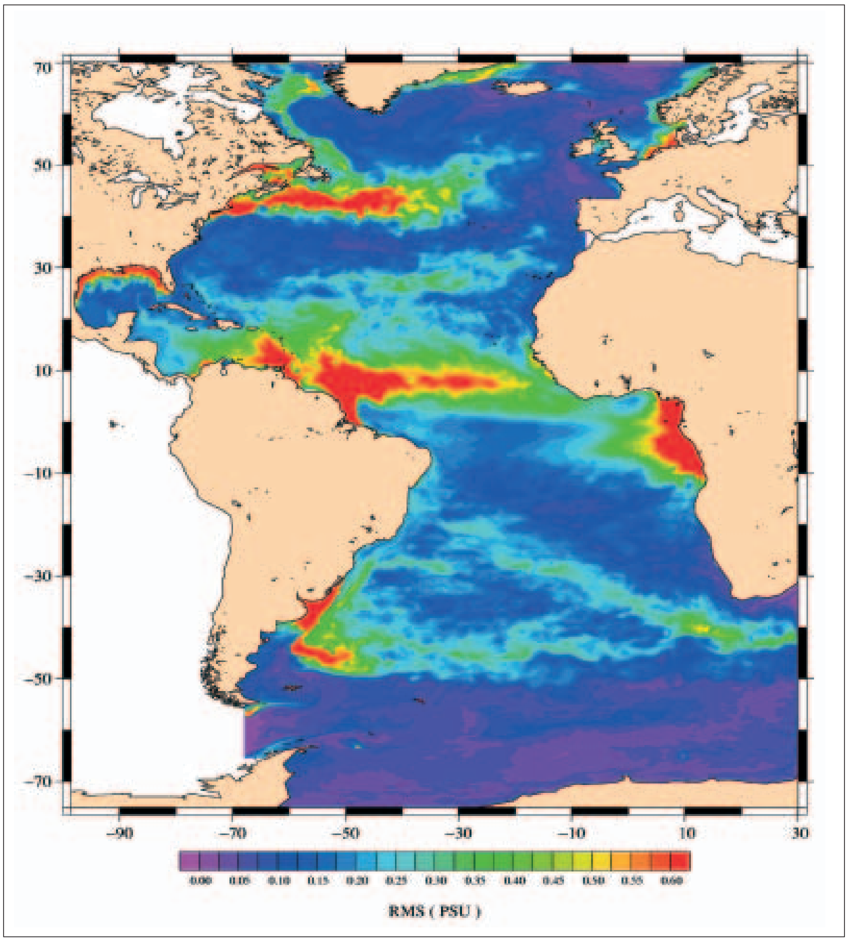

Figure 3. Expected Sea Surface Salinity (SSS) variations over a period of three years (five-day mean values from daily Clipper simulations, 1997-1999)

Salinity variations are in the range of 0.05 to 0.5 psu. Assuming the GODAE requirements could be met, most interesting salinity features would be detectable. However, these simulations show that also with reduced spatial resolution, seasonal features will be observed with much better accuracy than the present knowledge of global seasonal Sea Surface Salinity (SSS) variations. Significant improvements can be expected from SMOS for mesoscale features in the 200–300 km range. These features occur in tropical regions and involve strong salinity variations of up to 2 psu.

To study the sensitivity of brightness temperature (T_b) to wind velocity, SST and SSS, the UCL and Yueh-LODYC two-scale emissivity models were used. The impacts of different parameterisations for the modelling of the sea surface (sea-water permittivity, wave spectrum, foam coverage) and for the modelling of electromagnetic scattering in each of these models were analysed. The results are summarised in Table 1.

Table 1. Influence of various sea-surface parameters on brightness temperature (T_b) for various parameterisations in two-scale Yueh-LODYC and UCL models

δTb/δSSS (K/psu)	0.7 at 30°C to 0.25 at 0°C ~1 K bias : Ellison > Klein & Swift
δTb/δSST (K/°C)	0 at 15°C to 0.13 at 30°C
δTb/δ (K/m/s)	Without foam, at nadir : 0. to 0.24 K/m/s
Upwind-downwind asymmetry	For _< 30° U < 15 m s^{-1} , less than ±0.1K At = 50º U = 15 m/s, ±0.1 K/m/s to ±0.4K/m/s depending on wave spectrum
Upwind-crosswind asymmetry	< ± 0.1K to ± 0.4 K depending on wave spectrum
Foam effect	< 0.1K below 7 m/s for U >10 m/s several K differences between various parameterisations

The results show that there is a need to improve the modelling of the surface-roughness effect and the foam effect, both effects being modelled with an uncertainty larger than 1 K for commonly encountered oceanic situations. Modelling of the permittivity is also critical.

New models for the foam emissivity and coverage have been developed within the study, which still need to be validated. Preliminary results indicate a relatively small foam emissivity at L-band for wind speeds lower than 12 m/s. Comparisons between T_b simulated with the UCL and Yueh-LODYC emissivity models and WISE 2000 measurements (see below) indicate a better agreement of models that predict a higher sensitivities of T_b to the wind speed. It should be noted, however, that possible disturbances of the wind/wave field due to the platform and due to limited fetch have not been accounted for. In further studies, such effects would need to be accounted for before extrapolating these conclusions to a model run in open-ocean conditions. A more complete set of measurements describing the sea state has been acquired during the WISE 2001 campaign, which should help in interpreting the L-band measurements.

Moreover, further campaigns are needed in the open ocean to validate these results, which were obtained in a limited fetch area. In this respect, the EuroSTARRS measurements made in the Atlantic Ocean (Gulf of Gascogne) in November 2001 are very useful.

The impact of the sea-surface temperature diurnal cycle was also investigated, using the cool-skin and warm-layer model of Fairall et al. Under realistic wind-speed and SST conditions, non-negligible effects appear in some parts of the ocean during the evening orbit: the SST diurnal variation averaged over 10 days may reach 1.5ºC in regions of very low wind speed, leading to SSS biases of up to 0.4 psu. Therefore, when dealing with SMOS measurements made during evening orbits, it will be necessary to correct for this effect.

The impact of rain at 1.4 GHz on the brightness temperatures at satellite altitude was also investigated. It might be important because of its high variability compared to the sensitivity of brightness temperature to changes in surface salinity. The Mie scattering calculations show that at 1.4 GHz only the extinction of water seems to be important. The extinction for water and ice is two orders of magnitude smaller than at 10.7 GHz. For an assumed rain rate of ~9 mm/h and a rain-layer thickness of ~8 km, the maximum atmospheric contributions occur at 50 deg incidence angle with a signal contribution of 4.2% and 7.1% for the upward emission, and 4.5% and 10.4% for the reflected downward emission with vertical and horizontal polarisations, respectively (values given as a percentage of the total signal at satellite altitude). The rain effect causes a bias in the brightness temperature that is almost independent of all surface parameters. Integration over the different SMOS footprint sizes will minimise this effect, especially in the case of inhomogeneous beam filling. However, it should be included in forward radiative-transport calculations.

A first estimate of the salinity retrieval error linked to noise on brightness temperature measured in the SMOS configuration, and to noise on ancillary parameters (wind and SST), was made. Using a retrieval of sea-surface salinity at each satellite pass to account for wind variability from one pass to another, the error on the SSS averaged over 10 days and 200 km was estimated to be less than 0.1 psu. For this preliminary estimate, errors due to image reconstruction were neglected and it was assumed that all errors are uncorrelated. Further studies are needed to investigate the consequences of these hypotheses.

The Ocean Salinity Retrieval Study

The ocean-salinity retrieval study is designed to advance the understanding of the physics of the SMOS characteristics (L-band, range of incidence angle, dual polarisation) for different sea-state conditions, and to develop retrieval algorithms for ocean salinity from SMOS observations, accounting for the spatial resolution (varying footprints), mixed pixels due to wind variability, foam, as well as the timeliness and accuracy of ancillary data. The prime contractor is CLS of France. The activity, which was started in July 2001 and will last for one year, embraces the following tasks:

- Extension of the modelling exercise of the previous study.
- Validation of the models developed.
- Improvement of models accounting for SMOS characteristics (footprint, auxiliary data).
- Analysis of standard retrieval techniques.
- First steps towards an assimilation scheme – improved retrieval techniques.

The electromagnetic part of the new emission model uses the recently developed Small Slope Approximation (SSA), at second and third order. This yields the first three harmonics of the brightness temperatures for the four Stokes parameters. For the background of surface waves with small slopes, the spectral model of

Kudryatsev et al. is used. Reduced bi-spectrum and hydrodynamic modulation transfer functions follow the models of Yueh and the hydrodynamic theory of Elfouhaily et al. The locally distributed breaking events are described by using the slope probability density function as introduced by Chapron et al. Ensemble averages are computed using a new foam coverage model. Outputs from this complete emissivity model have been compared to those from other available models and to experimental measurements made at higher frequencies. Comparisons for a few typical salinity, wind-speed and temperature conditions show relatively good agreement.

Sensitivity of the modelled brightness temperatures to the surface wind speed for different incidence angles has been compared to the WISE measurements (see below) as well as to previous observations made at L-band. Sensitivities obtained with the SSA model are mostly (H and V polarisations, incidence angles between 25° and 65°) in very good agreement with the WISE and Hollinger measurements. Absolute validation of the brightness temperatures has been performed. The simulated brightness temperatures for V polarisation are consistent with measured L-band radiometric measurements. For H polarization, a bias of 3 K appears, but this has to be carefully considered due to the very few measurements made in this polarisation.

The critical part of the validation is that of the sub-models (surface spectrum and foam coverage). Validation of the models used to describe the surface topography has not been possible yet. The foam-coverage model used in the SSA model has nevertheless been validated using video-camera data, which is in very good agreement with other empirical models.

Figure 4. The Casablanca oil rig

ESA's SMOS campaigns

In order to analyse signal dependence and to validate existing and improved models, three campaigns were conducted during the Phase-A study: the WInd and Salinity Experiment (WISE), the L-band Ocean Salinity Campaign (LOSAC), and the EuroSTARRS Campaign.

WISE

The WISE campaign was conducted in 2000 and 2001 from an oil rig (Casablanca Tower) about 50 km off the coast of Tarragona, in the northwest Mediterranean (Fig. 4). The overall objective was to measure and analyse polarimetric L-band emission under varying incidence and azimuthal viewing angles for a wide range of sea-state conditions. The LAURA L-band radiometer of the Polytechnic University of Catalonia (UPC), Spain, at the same time prime contractor and responsible for all logistics, was used as the core instrument (Fig. 5). In addition, a polarimetric Ka-band radiometer, a video system (for foam estimation), an infrared radiometer (for SST estimation) and a stereo-camera (for sea-surface topography estimation), as well as four oceanographic and meteorological buoys, were deployed. Systematic measurements were acquired from 16 November to 18 December 2000, and from 9 to 15 January 2001. The experiment was repeated from 23 October to 22 November 2001, to cover stronger winds and avoid interferences (RFI problems) encountered during the first campaign, which probably originated from airport radar systems. Data were recorded for wind speeds higher than 50 knots (~100 km/h), during one of the most severe storms this region ever had (Fig. 6). In addition, this experiment was coordinated with the EuroSTARRS (see below) campaign, which enabled contemporaneous data acquisition during an overflight of the STARRS instrument. These data are still being analysed, but the first preliminary results are presented below.

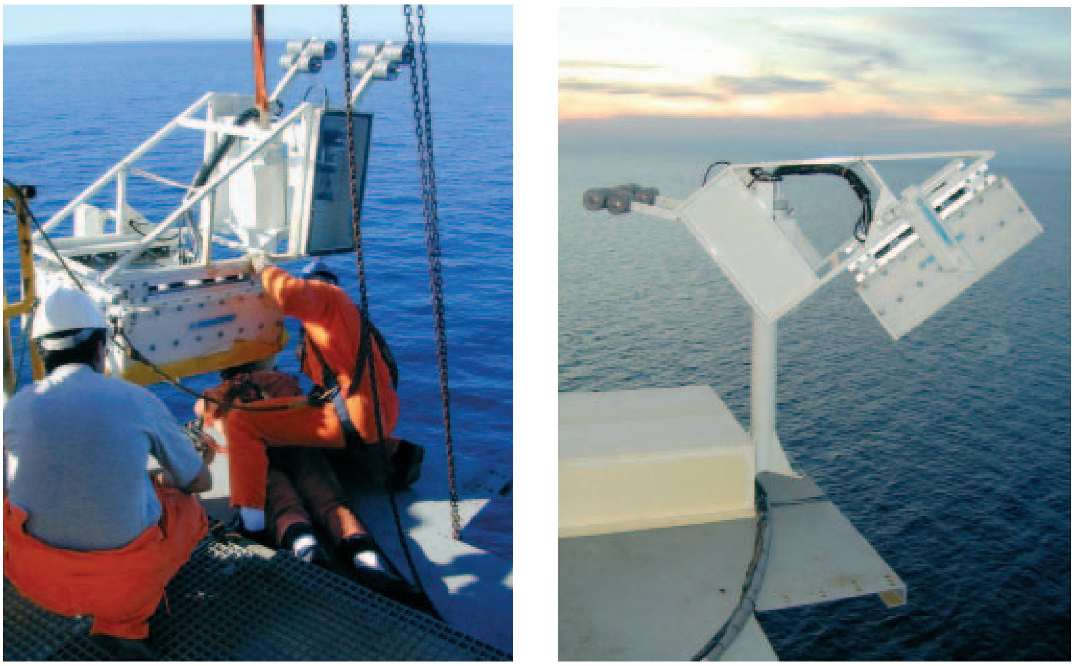

Figure 5a. LAURA during its installation on the Casablanca oil rig, 32 m above the sea surface, and during measurement taking on a calm day

The brightness temperatures' sensitivities to wind speed derived from WISE-2000 data confirm existing experimental data and are in agreement with numerical results predicted by the Yueh-LODYC two-scale model emissivity using the Durden and Vesecky (1985) sea spectrum multiplied by a factor of two. The experimental results show a sensitivity that, extrapolated at nadir, is about 0.22 K/(m/s), increasing with incidence angle for horizontal polarisation, and decreasing with incidence angle for vertical polarisation, being zero around 55° – 60°. The azimuthal variation is small, being approximately 0.1 – 0.2 K at low-to-moderate wind speeds, but up to 3 – 4 K peak-to-peak variations were measured during the night of 10 November 2001, a situation similar to that shown in Figures 6, with lower wind speed but greater significant wave heights (>11 m). WISE 2001 data is being analysed to improve the determination of the radiometric sensitivities to wind speed (notably via surface roughness and foam coverage), mainly at large incidence angles.

These results have been applied to a performance study of a SMOS-oriented sea-surface salinity retrieval algorithm. To avoid geometrical and Faraday-rotation polarisation mixing, the algorithm is based on minimisation of the error between the sums of the measured and the modelled T_h and T_v, for different pixel tracks in the alias-free field of view. Except for low sea-surface salinities and temperatures, the retrieved salinities have a root-mean-square error of approximately 1 psu for one satellite passage. Further research will focus on possible error reduction using several satellite passages within a 10 to 30 day interval, on the assumption that the error contributions from individual pixels are random.

LOSAC

The LOSAC campaign was initiated to address azimuthal dependence of the first two Stokes parameters ($T_{b,v}$ and $T_{b,h}$) on wind speed and direction, which is not yet fully understood. The EMIRAD full-polarimetric L-band radiometer was exploited aboard a C130 aircraft operated

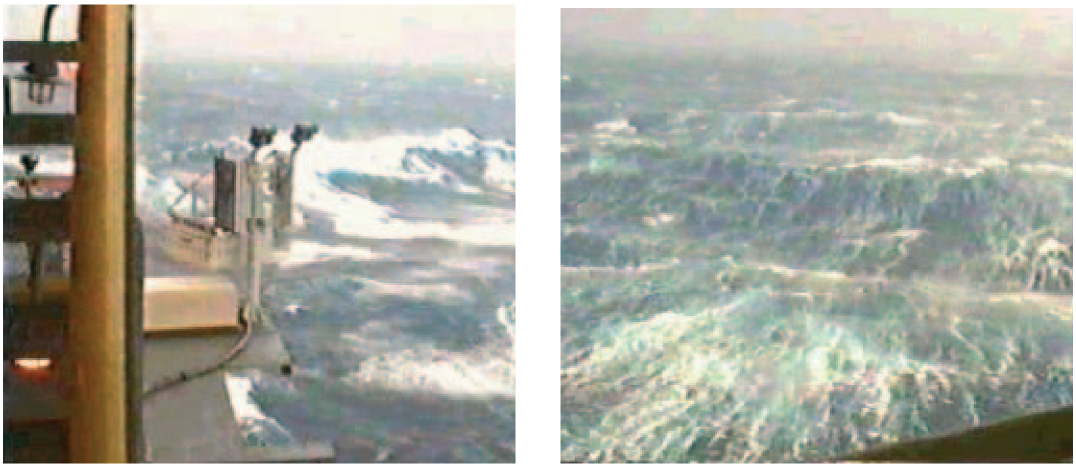

Figure 6. Rough seas during the storm on 15 November 2001, when the wind speed recorded by the platform's meteorological station 70 m above the sea surface exceeded 76 knots

by the Royal Danish Air Force over the North Sea. The instrument is owned by the Technical University of Denmark (TUD), which acted as prime contractor for this experiment.

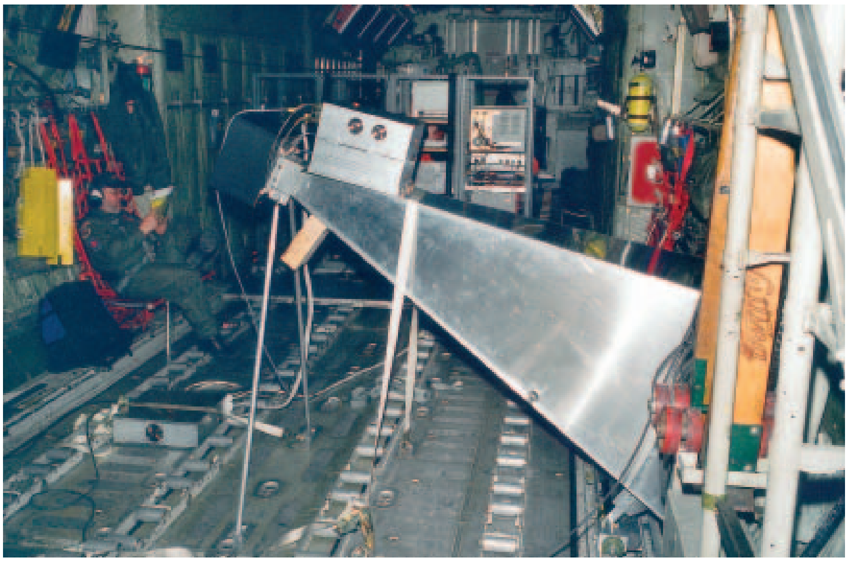

Figure 7. EMIRAD aboard the Hercules C130 aircraft

EMIRAD's large antenna horn looked out through the starboard parachute door (Fig. 7), an optimised installation for investigating azimuthal signatures by flying circuits with the antenna pointing at the sea surface. By changing the roll angle of the aircraft and thus the diameter of the circle of flight, data could be acquired for different antenna-beam incidence angles. A first technical test flight carried out on 16 January 2001 revealed technical problems due to RFI, which could be solved by additional shielding. Three science flights were subsequently conducted over the North Sea, on 15 and 23 March and 25 October. Additional flights are planned over the North Sea, and possibly over the North Atlantic.

Preliminary data analysis indicates a rather unstable situation regarding azimuthal signatures. In most cases there is no clear signal, but in some cases we observe that during a sequence of equal circuits, a clear azimuth signal can be present on one or even two circuits, yet disappears on the third. Figure 8 shows the corresponding result when the azimuthal signal is present. This example shows a clear 1 K peak-to-peak signal, but on the next circuit it has gone.

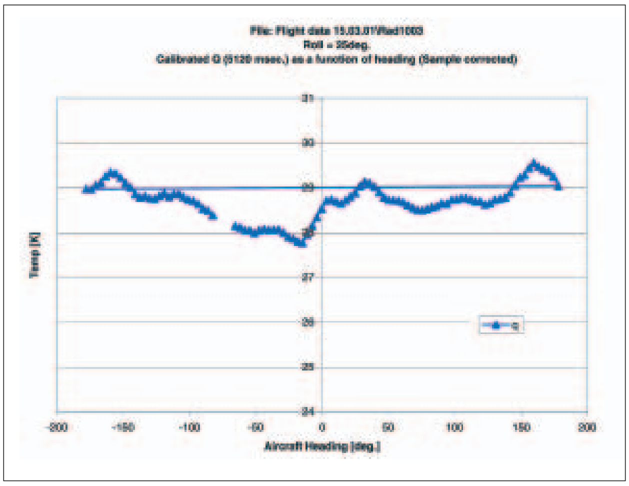

Figure 8. Second Stokes parameter as a function of aircraft heading (uncalibrated)

The L-band response to waves is poorly understood (L-band wavelengths are too long for capillary waves, yet too short for normal gravity waves), but it has been suggested that trains or packets of swell travelling in and out of the radiometer footprint may be responsible for the behaviour. In that case, it will never have any influence on SMOS, bearing in mind its 50 km footprint integrating over huge areas compared to an airborne system which typically has a 500 m footprint. Further analysis is ongoing.

EuroSTARRS

The main objective of the first exploitation of the Salinity Temperature and Roughness Remote Scanner (STARRS) in Europe (EuroSTARRS 2001) was to acquire SMOS-like observations for addressing a range of critical issues relevant to the soil-moisture objectives of the SMOS mission. Additional flights could be booked for ocean-salinity experiments and were coordinated with on-going campaign activities. The STARRS is owned by NRL (USA) and was operated during the campaign aboard a Dornier 228 by DLR, Oberpfaffenhofen (Germany). The instrument, a push-broom scanner with six beams, was mounted perpendicular to the flight direction and tilted to one side by 12° (Fig. 9). By overlapping flight patterns and accounting for the incidence angles of the different antenna beams, multi-angular observations up to 50° could be obtained. This required almost perfect flight navigation, which was supported by a new navigation system within the DLR aircraft.

Two flight paths were flown to support the ocean-salinity community: one along the shoreline from Bordeaux to the mouth of the Gironde river and outbound towards the Gascogne meteorological buoy located in the middle of the Bay of Biscay, and another from Barcelona to the Casablanca Tower. Circular flights with bank angles of 22° were performed over the Gascogne buoy and Casablanca Tower. Synoptic, along-track in-situ salinity and sea-surface-temperature measurements were acquired from research vessels operating at the same time. Both flights were made at sunset to avoid sun glint and took place on 17 and 21 November.

The first results are encouraging, although there are still some problems with the calibration of one antenna beam. Data analysis is currently ongoing.

Summary and outlook

Various science preparatory activities were initiated during the Phase-A studies to advance the science underlying the ocean-salinity objectives of the SMOS mission. The preliminary results can be summarised as follows:

Emissivity models: Uncertainties are introduced both by the complexity of the sea-surface structure, which depends mostly on wind speed, and by errors in the estimation of the dielectric constant at L-band. Models currently available simulate brightness temperature biased by up to 1.5 K. This bias varies with temperature and salinity. First results show a stronger confidence in the Klein and Swift model.

Wind speed – surface roughness: The change in emissivity due to the presence of sea-surface roughness is still poorly characterised, although it is large compared to the SSS signal: according to theoretical emissivity models, a 8 m/s wind speed changes Tb at nadir by 1 to 2 K, depending on the wave spectrum that is used. WISE 2000 measurements indicate that models and measurements do not disagree. Better constraints on emissivity models are expected from WISE 2001 and EuroSTARRS 2001 measurements.

Wind – azimuthal dependence: An azimuthal dependence on wind could not be confirmed for low wind speeds. This issue will be further investigated using the data acquired during WISE 2001, where measurements were made at high wind speeds.

Wind – foam: A physically-based foam coverage model has been developed within the Salinity Data Processing study. A foam model developed within the ocean-salinity requirement study showed that only thick foam (> 2 cm) contributes to the signal, but the signal level itself is still unknown. A foam experiment using a pond with a foam generator was proposed. The requirements for this experiment are currently being evaluated.

Sea-surface temperature: Sea-surface temperature should be available from complementary sensors with high accuracy (< 0.5 K). First study results show that diurnal variability is not critical, but needs to be corrected.

Faraday rotation: Various options (GPS measurements and TEC models, the use of the 1st Stokes, etc.) for correcting the Faraday rotation are considered. In addition, SMOS also provides a full-polarisation data-acquisition mode. Associated uncertainties and their impact on the retrieval accuracies still need to be analysed.

Timeliness of auxiliary information: As mentioned above, diurnal sea-surface-temperature variations are not critical, but the accuracy and timeliness of wind measurements and the associated effects (wave spectra, sun glint, foam) are critical. More insights are expected from the ocean-salinity retrieval study.

The dedicated campaigns performed during the Phase-A studies have provided suitable data for further analysis, in which particular emphasis should be placed on the enhancement of wave spectra and foam models, their relationship to wind parameters, and the associated uncertainties. This is particularly important in order to estimate the accuracy that could be achieved by aggregating salinity observations over space and time. In addition, more focus needs to be given to system accuracy and stability, and a suitable vicarious calibration scheme using the fleet of buoys that should be operational by the time SMOS is in orbit.

Acknowledgement

The authors would like to express their gratitude to the study and campaign teams and to the SMOS Science Advisory Group for their invaluable contributions.

Figure 9. STARRS mounted on the DO228 aircraft in data-acquisition configuration (tilted). For take-off and landing, the instrument was moved into a horizontal position using a winding device specially designed for this campaign

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