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The WISE 2000 Campaign: Sea Surface Salinity and Wind Retrievals from L-Band Radiometry

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ABSTRACT

Sea surface salinity (SSS) has been recognized as a key parameter in climatological studies. SSS can be measured by passive microwave remote sensing at L band, where the sensitivity of the brightness temperatures (T_v and T_h) shows a maximum and the atmosphere is almost transparent. To provide global coverage of this basic parameter (and also of soil moisture) with a 3-day revisit time, the SMOS mission was recently selected by ESA within the frame of the Earth Explorer Opportunity Missions. The SMOS mission will carry the MIRAS instrument, the first two-dimensional L-band aperture synthesis interferometric radiometer. To address new challenges that this mission presents, such as incidence angle variation with pixel, polarization mixing, effect of wind and foam and others, a measurement campaign is being sponsored by ESA under the name of WISE 2000 (Wind and Salinity Experiment) and it is scheduled for October-November 2000. Two L-band radiometers, a video, a IR and a stereo-camera and four oceanographic and meteorological buoys will be installed in the oil platform "Casablanca" located at 40 Km off the coast of Tarragona (Spain), where the sea conditions are representative of the Mediterranean open sea with periodic influence of the Ebro river fresh water plume.

Keywords: Passive Remote Sensing. L-Band radiometry. Salinity. Campaigns

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Sea surface salinity (SSS) distribution in the oceans and its annual and inter-annual variability, are crucial in understanding the role of the ocean in the climate system¹. Ocean circulation is mainly driven by the momentum and heat fluxes through the atmosphere-ocean interface, which can be traced by observation of SSS. In addition, salinity also determines ocean density and hence thermohaline circulation. In some regions (e.g. the Arctic), salinity is the most important variable as it controls processes such as deep water formation which is a key component in the ocean thermohaline circulation «conveyor belt». Ocean salinity is also related to the oceanic carbon cycle. Therefore, the assimilation of SSS into global ocean bio-geo-chemical models could improve estimates of the absorption of CO₂ by the oceans.

Monitoring SSS could also be used to improve the quality of ENSO (El Niño - Southern Oscillation) prediction by numerical models. Presently the models assimilate temperature and/or altimeter-derived sea level data only. The lack of salinity measurements results in major discrepancies between modeled and observed salinity units) error accounts for a 3.8 cm/s error in geostrophic velocity at 1 km depth calculated from the corresponding surface value. This is particularly important in the Western Equatorial Pacific where there is a strong ENSO-related near-surface salinity signal and where zonal advection is of major importance for ENSO mechanisms.

SSS is correlated with estimates of the net evaporation minus precipitation (E-P) balance. (E-P) is difficult to measure accurately over the ocean, so global maps of SSS would provide a constraint on estimates of (E-P) on the global scale. This would give insights into the phenomena driving the thermohaline circulation and also allow validating latent heat flux estimates. The water flux through the sea surface layers is critical for density stratification and strongly influences the mixed layer depth and the intensity of surface currents.

Even though the importance of SSS is well recognized, at present it is a parameter not routinely measured by any sensor at a global scale. The SMOS (Soil Moisture and Ocean Salinity) mission was selected by the European Space Agency as the second Earth Explorer Opportunity with a launch date in June 2005. The sensor aboard SMOS is MIRAS (Microwave Imaging Radiometer with Aperture Synthesis) a dual-polarization L-band radiometer with full polarimetric capability. The measurement of Ocean Salinity is one of the challenges of this mission.

2. THE SMOS/MIRAS CONFIGURATION

The MIRAS instrument is the first two-dimensional imaging interferometric radiometer and it will be boarded in the SMOS mission². It consists of a total of 81 small antenna receivers uniformly arranged on a Y-shaped array, and a total power radiometer (noise-injection) in its center for absolute calibration (Fig. 1). To avoid aliasing during the image formation process, the minimum antenna spacing for this configuration is $\lambda/\sqrt{3}=0.57\lambda$, being λ the wavelength at the center frequency (1413.5 MHz).

Figure 1. MIRAS instrument artist's view (courtesy of CASA, Spain)

Due to the high brightness temperature contrast between the Earth and the sky, a limited amount of aliasing is permitted, as long as only affects the sky and some parts of the Earth at high incidence angles and/or at large distance with respect to the satellite ground-track. Consequently, the selected antenna spacing is set to 0.89λ , which for 27 antennas per arm gives a total arm length of about 5.2 m, that corresponds to an angular resolution of less than 2°. The MIRAS instrument will be put on a small satellite on low Earth sun-synchronous orbit with the antenna boresight tilted with respect to nadir, so the angular resolution translates to a ground spatial resolution better than 50 Km. The instrument will be periodically calibrated using a distributed noise injection network in combination with a highly stable noise injection radiometer. It is expected that this technique will provide absolute radiometric accuracy below 2 K.

The alias-free on-ground field of view of the instrument has a distorted hexagon shape with curved sides, having each pixel different sizes and incidence angles (Fig.2). A snap-shot brightness temperature map of this field of view is obtained each 0.78 s, with an average radiometric resolution of about 5 K over 200K³. Radiometric sensitivity of out-of-boresight pixels is degraded by the antenna pattern.

Figure 2. Typical MIRAS Field of View (courtesy CASA and GMV) represented in the direction cosines domain.

Figure 3. Typical MIRAS alias-free Field of View, ground incidence angle and pixel size represented in ground coordinates (www-sv.cict.fr/cesbio/smos/). A point over the Earth surface is observed under different incidence and azimuth angles with different spatial resolutions.

Due to the motion of the platform, each pixel is measured several times with different spatial and radiometric resolution and incidence angle (Fig.3). Provided good models exist to account for these varying measuring conditions, the salinity map can be obtained by averaging out all the retrieved values at each snap-shot. The minimum field-of-view (FOV) in the along-track dimension is about 800 Km, which at 7 km/s corresponds to 114 s, or 146 snap-shots of 0.78 s each. The equivalent radiometric resolution turns to be 0.4 K, corresponding to a single-pass salinity resolution of 0.8 psu at 20 °C or 1.6 psu at 0 °C. However, in the center of the FOV, the total along track distance is about 1.400 km, giving 0.6 and 1.2 psu salinity resolutions. To improve these figures, averaging of different pixels or satellite passes is needed, which can be done due to the slow time-space variation of salinity in open ocean.

3. THE EMISSIVITY OF THE OCEAN AT L-BAND

The dielectric constant for seawater is determined, among other variables, by salinity. In principle it is possible to retrieve SSS from microwave measurements as long as variables influencing the brightness temperature (T_B) signal (SST, roughness, foam,) can be accounted for e.g. by the use of different viewing angles, polarization and frequencies. The sensitivity of T_B to SSS is maximum at low microwave frequencies and the good conditions for salinity retrieval are found at L-band (1.4 GHz, 21cm wavelength). However, it must be stressed that at this frequency the sensitivity of T_B to SSS is low (0.5K per psu for a SST of 20°C, decreasing to 0.25K per psu for an SST of 0°), placing demanding requirements on the performance of the instrument (Fig. 4).

Due to this low sensitivity, and the spatial resolution that can be expected with a spaceborne microwave interferometric radiometer, we are still not in a position to obtain SSS data for mesoscale or regional studies. However, several phenomena extremely relevant for large-scale and climatic studies can benefit from such an observation approach: barrier layer effects on tropical Pacific heat flux, halosteric adjustment of heat storage from sea level, North Atlantic thermohaline circulation,

surface freshwater flux balance, etc. Considering the resolution constrains the overall goal for SSS retrieval from SMOS data is to meet the GODAE (Global Ocean Data Assimilation Experiment) optimized requirement for open ocean SSS: a resolution of 0.1 psu over 200 km boxes every 10 days.

Figure 4. Brightness temperature of the sea. Observation angle = 0°, wind speed = 0 m/s.

The emissivity of the sea surface is a function of salinity, temperature and wind speed as a minor parameter. The best sensitivity to the OS is obtained at 1431.5 MHz, however, even though the sensitivity to sea surface temperature at 35 psu sea salinity is minimum (~ 1.2 K for SST from 0 to 40°C) the influence of sea temperature can not be neglected even at these frequencies. Hence, the measurement of the ocean salinity requires the use of another spacecraft, which allows the retrieval of SST.

Figure 5 shows the simulated variation of the vertical and horizontal brightness temperatures at 1413.5 MHz for different wind speeds and observation angles from 0 to 65°, which covers the maximum range of incidence angles that can be observed by the MIRAS instrument (Fig. 3). Sea surface temperature is 15°C and sea surface salinity is 36 psu. The different brightness temperatures between H and V polarizations is expected to improve the rejection of pixels affected by sun glitter. The brightness temperature increase due to wind speed decreases with observation angle, and it is negligible around 65° at vertical polarization. At horizontal polarization, the effect of wind speed produces a monotonic increase of the brightness temperature. Near nadir the sensitivity to wind speed is ~ 0.2 K/(m/s).

a)

b)

Figure 5. Simulated vertical and horizontal brightness temperature versus observation angles. Azimuth angle = 0° (up-wind direction), wind speed: 0 m/s (solid line), 5 m/s (dashed line), 10 m/s (dash-dot line) and 15 m/s (dotted line). Note that at $\phi = 0^\circ$, T_h slightly decreases with wind speed, and then increases, which is due to the azimuthal modulation.

In addition to the variation of the brightness temperatures with the observation angle, in the last decade it has been shown that an azimuthal signature exists⁴. The amplitude of these signatures at 19 and 37 GHz is about 1 to 2 K for wind speeds of 10 m/s. At L-band it is expected to be smaller, but not negligible for accurate sea surface salinity retrievals. Large differences exist between models, but it is expected that the amplitude of the variation is about 0.2 – 0.5 K at 10 m/s. Figure 6 shows their simulated variation⁵ with respect to azimuth angle (measured with respect to the up-wind direction). In addition, to the signature in T_h and T_v , a signature also exists in the third Stokes parameter ($U = 2\Re\{E_v E_h^*\}$).

Figure 6. Simulated azimuthal dependence of the first three Stokes parameters versus observation angle and wind speed: a-d) T_h , e-h) T_v , and i-l) U . Observation angle: a,e,i) 20° , b,f,j) 35° , c,g,k) 50° and d,h,l) 65° . Wind speed: 5 m/s (solid line), 10 m/s (dashed line), and 15 m/s (dash-dot line).

4. THE WISE 2000 CAMPAIGN: SCIENTIFIC OBJECTIVES, DESCRIPTION OF THE INSTRUMENTS AND MEASUREMENT STRATEGY

Scientific Objectives- The scanning configuration of the SMOS/MIRAS presents new challenges. Some of them will be addressed during the WISE 2000 campaign:

- i) Two-dimensional imaging of the scene, with varying incidence angles and pixel resolution as the pixel travels through the alias-free field of view.
- ii) Polarization mixing between vertical and horizontal polarizations due to the relative orientation between the antenna reference frame and the pixel's local reference frame.
- iii) Not yet well understood azimuthal dependence of the first two Stokes parameters (T_v and T_h) with wind direction.
- iv) Unknown signature of the third and fourth (U and V) Stokes parameters and their azimuth/elevation dependence with wind speed. No experimental measurements have been yet obtained.
- v) Effect of sea foam at L-band.
- vi) Feasibility of accurate retrieval of U, and eventually V, assuming that Faraday rotation effects (for a satellite borne sensor) have been corrected for by other means.

The objective of the WISE experiment is to address points (i), (iii), (iv) and (v) by collecting experimental data under the widest possible range of conditions so as to improve and refine existing models or others that could eventually be developed during this project.

The *Casablanca* oil platform that the petrol company Repsol owns 40 km away from the Ebro river mouth in Spain (Fig. 7) is an optimum location for this experiment. In this site wind intensities as high as 90 km/h (25 m/s) are not uncommon during the months of October and November (Fig. 8) when the campaign is foreseen to take place, provided the drilling activities of the company scheduled for this spring-summer are carried out on time.

Figure 7. Location of the Casablanca platform.

Figure 8. Occurrence of strong NW and NE winds in autumn: 6 hour wind speeds at the Casablanca platform, October-December 1992.

Description of the instruments- The required measurements will be obtained from the following instrumentation:

- Two L-band radiometers: a dual polarization radiometer (T_h and T_v) from the University of Massachusetts at Amherst (UMass), USA, and a fully polarimetric radiometer (T_h , T_v , U and V) from the Polytechnic University of Catalonia at Barcelona (UPC), Spain,
- Four oceanographic buoys from the Institut de Ciències del Mar (ICM), Spain, and the Laboratoire d'Océanographie Dynamique et de Climatologie (LODYC), France, that will measure sea surface salinity (SSS), sea surface temperature (SST), wind speed (WS), wind direction (WD), wave height (WH), wave period (WP)...
- Portable meteorological station from UPC, that will measure atmospheric pressure, temperature, relative humidity and rain rate.
- Stereo-camera from LODYC that will provide 3D images of the sea surface to determine the foam coverage and sea surface rms slopes
- Video images of the antenna boresight from a video camera mounted on UPC radiometer.
- Infrared radiometer from the University of Valencia, Spain, that will provide SST estimates.

Figure 9. Lateral view of the Casablanca Platform indicating the location of the instrumentation.

In order to properly calibrate the radiometers the antenna boresight must be pointed to the zenith (or close to). Since the helipad must be free of obstacles, the radiometer will be placed at a lower floor with zenith visibility. Another objective of the WISE 2000 experiment is the measurement of the azimuthal signature of T_v , T_h and U (and eventually V , if detectable with instrument resolution). Taking into account the limitations imposed by measuring from a fixed platform, the range of incidence angles is limited to approximately $20^\circ \leq \theta \leq 180^\circ$ (0° = nadir, 90° = horizon, 180° = zenith), and larger than $0^\circ \leq \phi \leq 180^\circ$ in azimuth. The UPC meteorological station will be located as close as possible to the radiometers, and closer than 25 m from the data acquisition system located in the platform control room. Its purpose is to get real time data mainly on wind speed and direction for antenna safety and to rain rate data not available from other meteorological stations.

Four buoys will be moored at 200 m of the Casablanca oil platform in the North side. They will measure:

- BUOY 1 must collect conductivity and temperature data near the sea surface and send it to a data logging station installed on the platform, using a real time link.
- BUOY 2 is a meteorological and physical oceanographic data measuring system, with data storage and also a radio link to the same data logging station on the platform. From the platform and in parallel with the radiometric measurements, a regular sampling of surface and sub-surface seawater will be carried on, using one Niskin type sampler hold by means of an electrical winch.
- BUOY 3 is a wave buoy of Spear-F type measuring the omnidirectional wave spectrum. It will be moored using a special cable that insures that the measured wave spectrum is not modified with respect to the results of a freely drifting buoy. The data are transmitted via the ARGOS system after onboard processing.
- BUOY 4 is a SVP drifter built by Clearwater, modified to be moored, which will measure the conductivity and the temperature of the surface water at about 20 cm depth. The data are transmitted via the ARGOS system.

Table 1 summarizes the main measurements and data products that will be measured during the WISE 2000 campaign.

Measurement strategy- Sea state variability is an important point and at present we can only rely on the stationarity of sea state, at the scales of interest, for about 5 minutes, although it might be more. Three modes of measurement are foreseen:

1) Mode 1, fixed observation: This is a mode for long observations at fixed direction (incidence and azimuth, the azimuth will vary with the wind direction) to study the time scale of the stability of the sea state and its consequences on L band emissivity.

2) Mode 2, azimuth scan: The range of angles to be swept must be as large as possible (within the limitations of not seeing neither the platform nor the sky). Since the amplitude of the azimuth variation is very small, it is foreseen a 30° step scan ($0^\circ, 30^\circ, 60^\circ, 90^\circ, 120^\circ, 150^\circ, 180^\circ$) in the following order: $0^\circ, 60^\circ, 120^\circ, 90^\circ, 180^\circ, 30^\circ, 90^\circ, 150^\circ$. Every measurement is 2 minutes long, plus 2 minutes of observation of the sky (zenith angle = observation angle) for galactic and atmospheric downwelling noise measurement.

3) Mode 3, elevation scan: It is proposed to scan the observation angles $20^\circ, 35^\circ, 50^\circ, 65^\circ$ in an interlaced way in the following order: $20^\circ, 50^\circ, 35^\circ$, and 65° . Every measurement is 2 minutes long, so as to have a large angular variation in a short period of time in which the seas state is stationary.

The measurement modes also apply in case of rain.

Table 1. Summary of key measurements and data products

Instrument	Params.	Description	Units	Comments	Resolution
L-band polarimetric radiometer and meteorological station #1 (UPC), Infrared radiometer (UV)	Time	Absolute GPS time	H, m, s	Tag all measurements for easier comparison	1 s
	Yaw	Antenna orientation ($\pm 180^\circ$)	deg	Measured with a 3 axes digital inclinometer located in the back side of the radiometer antenna (2 min integration time)	$< 0.1^\circ$
	Pieth	" ($\pm 180^\circ$)	deg		$< 0.1^\circ$
	Roll	" ($\pm 70^\circ$)	deg		$< 0.1^\circ$
	Th	Horizontal brightness temp.	K		0.02 K
	Tv	Vertical brightness temp.	K		0.02 K
	U	Third Stokes parameter	K		0.02 K
	V	Fourth Stokes parameter	K	V will not be delivered if it is not significant.	0.02 K
	WS	Wind speed	m/s	WS used only for safety purposes of the antenna in case of winds of very high intensity.	0.44 m/s
	WD	Wind direction	°		1°
	RH	Relative Humidity	%		1%
	RR	Rain Rate	mm/h		0.25 mm/h
	P	Atmospheric Pressure	mbar		1 mbar
	T	Atmospheric Temperature	°C	Used to determine fraction of foam sea coverage	0.05°C
	Video images	Video camera on antenna	K	Estimate SST for cross-check with satellite and ground truth data (1 s integration time)	0.05 K (sensit)
	IR images	IR camera on antenna (UV)			$< \pm 0.14$ K (acc.)
Oceanographic buoys (ICM+LODYC)	WS	Wind Speed	m/s	Range: 0.4 – 76 m/s	$\pm 2\%$
	WD	Wind Direction	°	Range: 0° - 360° referred to magnetic North	$\pm 5^\circ$
	T	Air Temperature	°C	Range: $-8^\circ\text{C} \dots 41^\circ\text{C}$	$\pm 0.1^\circ\text{C}$
	RH	Relative Humidity	%	Range: 0 – 100%	$\pm 3\%$
	SR	Solar Radiation	W/m ²	Range: 0 – 2000 W/m ²	± 0.4 W/m ²
	WH	Wave Height	m	Range: 0 – 10 m	$\pm 10\% \pm 0.2\text{m}$
	WP	Wave Period	s	Range: 1- 30 s	$\pm 10\%$
	CS	Current Speed	m/s	Range: 0 – 500 cm/s	± 2 cm/s
	CD	Current Direction	°	Range: 0° - 360° referred to magnetic North	$\pm 5^\circ$
	WT	Water Temperature	°C	Range: $-8^\circ\text{C} \dots 41^\circ\text{C}$	$\pm 0.1^\circ\text{C}$
	C(S)	Conductivity	S/m	Range: 0 – 7 S/m	0.0003 S/m
	H1/3	Significant wave height	m	Hourly spectrum in 30 frequency bands between 2.62 and 23.14s integrated during half an hour	832x624pixels
	P	Dominant period	s	23.14s integrated during half an hour	one pixel
	WSPEC	Wave spectrum	m ² /s	2 pictures every 10 or 2 min	minimum area 64 cm ² depending on slanting angle
	¹ Primary data	Digital pictures	Pixels		/ surface
	² Foam	2 x 1.4 Mbytes	%		about < 5 cm $>$
	³ Foam area	% pixels	%		
Stereo camera (LODYC)	⁴ Topography	Heights	cm	Depending on light intensity and contrasts	

5. CONCLUSIONS

This paper has described the importance of sea surface salinity measurements for a better understanding of the climate system. The configuration of the SMOS/MIRAS instrument, the first two-dimensional L-band aperture synthesis radiometer has been presented. It will allow to obtain for the first time the L-band radiometric data required to derive sea surface salinity over the oceans and soil moisture with over land, with global coverage and 3 day revisit time, with a spatial resolution better than 50 km. The particular configuration scan of this sensor, with varying pixel size and observation angles, poses new challenges that have to be addressed to improve the retrieval algorithms. The L-band emissivity of the sea has to be accurately known, including its dependence on the observation angles, surface temperature and salinity and wind speed and direction relative to the antenna boresight. To improve this understanding with actual data, the WISE 2000 campaign has been supported by the European Space Agency. Simulation results on the dependence of the first three Stokes elements (T_v , T_h and U) on these variables have been presented. They have been used in the optimization of the campaign measurement strategy. The required key measurements and the instrumentation have been described: two L-band radiometers, four oceanographic and meteorological buoys, a stereo-camera and a video and infrared cameras.

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