Wind Speed Effect on L-Band Brightness Temperature Inferred From EuroSTARRS and WISE 2001 Field Experiments

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***Abstract*—The results from two field experiments in the Mediterranean Sea are used to study the wind speed dependence of brightness temperature at L-band. During the EuroSTARRS airborne experiment, an L-band radiometer made measurements across a large wind speed gradient, enabling us to study this dependence at high wind speed. We compare our results with a two-scale emissivity model using several representations of the sea state spectrum. While the results are encouraging, unfortunately the accuracy of the measurements does not permit us to distinguish between the so-called twice Durden and Vesecky spectrum and the Elfouhaily spectrum above 7 $\mathrm{m \cdot s^{-1}}$. The effect of foam is certainly small. During the WISE 2001 field experiment carried on an oil rig, we studied this dependence at low wind speed, finding an abrupt decrease of the wind speed effect on the brightness temperature below 3 $\mathrm{m \cdot s^{-1}}$.**

***Index Terms*—Foam, L-band, radiometry, sea state spectrum, sea surface salinity, wave, wind.**

I. Introduction

SEA SURFACE salinity (SSS) is of primary importance to ocean circulation. On one hand, it is a driving force for thermohaline circulation; on another hand, it is a powerful tracer of water masses. Yet, at present, it is monitored at a reasonable sampling rate using ship measurements only in very limited areas of the global ocean; large parts of the ocean have never been measured [1]. The ARGO program aims at improving our knowledge of ocean salinity in the water column by deploying an array of 3000 profiling floats all over the ocean. Nevertheless, the ability to monitor surface salinity for years on a regular basis from satellite would be a significant improvement for the understanding of global ocean circulation and of its consequences for climate. Recent studies analyze the potential impact of satellite SSS and prove its usefulness for a better simulation of the oceanic mixed layer in the equatorial Pacific region [2] and for improving El Niño/Southern Oscillation (ENSO) predictions [3]. It is during the late 1960s that the possibility of a potential use of L-band (1.41 GHz) microwave radiometers to measure salinity came in, the first airborne measurement being made in 1970 [4]. However, only the recent arrival of two-dimensional synthetic aperture radiometers have made measurements in this wavelength range feasible with a reasonable spatial resolution. As a result, the Soil Moisture and Ocean Salinity mission (SMOS) (http://www.cesbio.ups-tlse.fr/fr/indexsmos.html) was selected to be launched in 2007 by the European Space Agency (ESA) in 1999. In preparing for the SMOS mission, ESA sponsored several field experiments in order to improve sea surface emissivity models in L-band: EuroSTARRS [5], WISE 2000 [6], and WISE 2001 [7]. In this paper, we address the issue of the effects of sea surface roughness and foam on emissivity.

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II. EuroSTARRS Campaign

This airborne experiment used the Salinity Temperature and Roughness Remote Scanner (STARRS) L-band radiometer from the Naval Research Laboratory (NRL). It was mounted on a Dornier 228 plane from the Deutschen Zentrum für Luft und Raumfahrt (DLR). One flight took place above the Gulf of Gascogne on November 17, 2001; another one was made above the Mediterranean Sea on November 21, 2001. Here, we will use the only measurements performed over a variable wind speed region: they were made over the Mediterranean Sea during the return flight from Barcelona to Munich on November 23, 2001. The flight track is shown on Fig. 1. The plane left the Spanish coast at 16h40 UT and reached the French coast at 17h49. The flight took place after sunset, thus avoiding sun glint.

A. Measurements During Transit Flight

1) Radiometer: During the transit, STARRS was mounted flat below the aircraft. The radiometer is a pushbroom instrument with a phased array that acquires data with six beams ori-

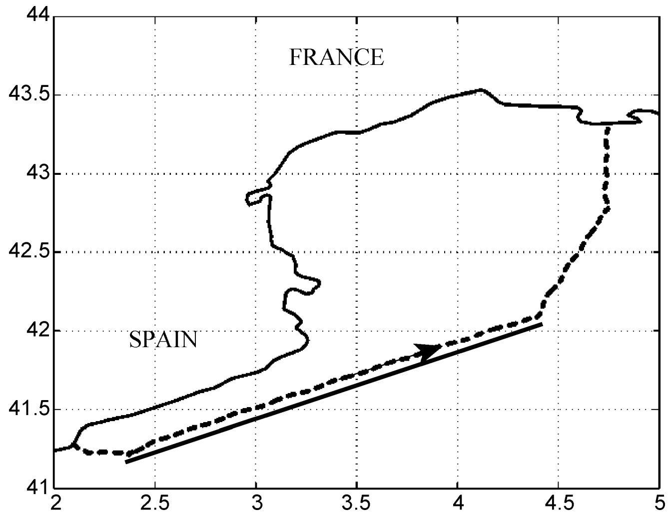

Fig. 1. Plane track (dashed line) during the EuroSTARRS transit. The double line shows the part of the flight used in this study.

ented almost perpendicular to the plane track simultaneously. The measurements are made only at vertical polarization, referred to the radiometer plane. When the radiometer is parallel to the sea surface, as it is the case during this flight, this is vertical polarization in the sea surface frame. Due to a hardware problem, the measurements were noisy, and we could use only the data from two antenna beams during the first part of the flight: we used measurements made between 16h53 (starting far from coast) and 17h20 (stopping before high noise); the doubled line in Fig. 1 shows the part of the flight used. Because of calibration problems on some antenna beams and receivers, we use only measurements from the directions 2L and 3R looking, respectively, at 21.5° left (off-nadir angle) and 38.4° right of the aircraft. The half-power beamwidth is 14.5° for the 2L antenna and 16.5° for the 3R one. The highest side lobe is 11 dB, and the beam efficiency is 89% and 90%, respectively.

2) Measurements of Geophysical Parameters: Since this flight was not planned as part of the experiment, no dedicated *in situ* measurements were made in support of the radiometer measurements. Therefore, we used data from the Observatoire de Recherche sur l'Environement SSS (ORE-SSS) program, which monitors the sea surface temperature (SST) and the SSS onboard ships of opportunity [8]. In addition, we obtained SST images from Airborne Very High Resolution Radiometer (AVHRR) local area coverage measurements and wind velocity from SeaWinds-on-QuikSCAT (QSCAT) scatterometer measurements.

M.S. Rome left Marseille toward the Strait of Gibraltar on November 28, five days after the flight. The measurements of SST and SSS made onboard are shown in Fig. 2(a) and (b). Between 41°N and 42.88°N in the latitude band overflown by the plane, the SST measured by the ship varied between 13.4 °C and 15.8 °C, with a minimum around 42 °N. Since SST can vary rapidly, we checked with SST retrieved from AVHRR measurements at 2-km resolution by the SATMOS data bank (www.satmos.meteo.fr/html/SATELLITE.html). The composite image of the measurements made on November 22 and 23 is shown in Fig. 3 being in qualitative agreement with the ship results, with a minimum in the middle of the journey.

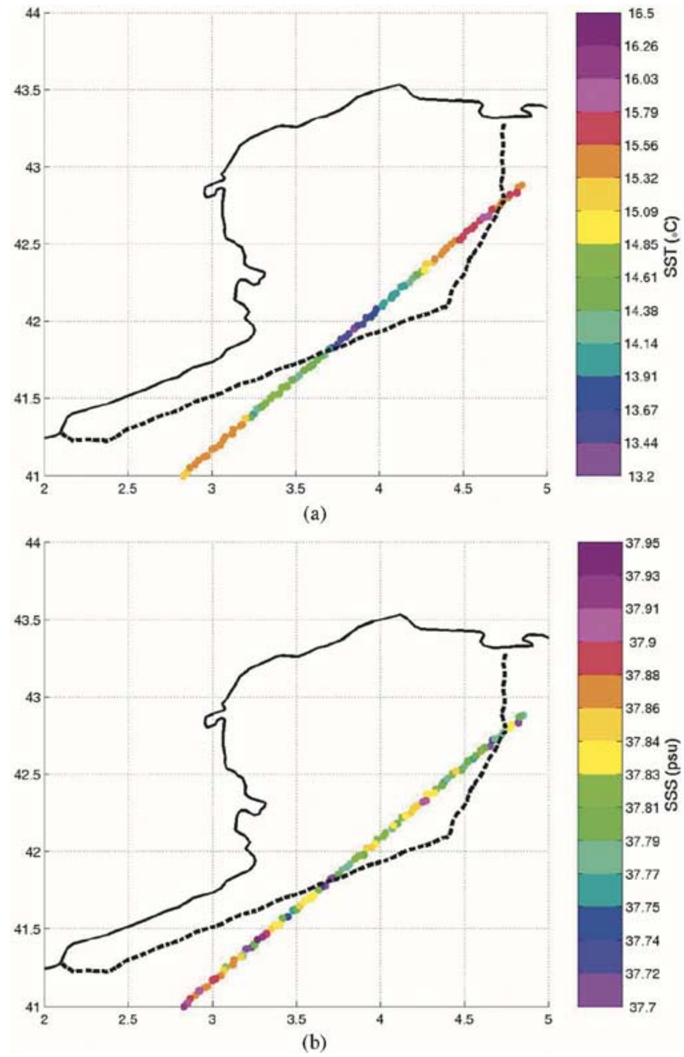

Fig. 2. Color-coded ship measurements of (a) SST and (b) SSS. The plane track is superimposed (dashed line).

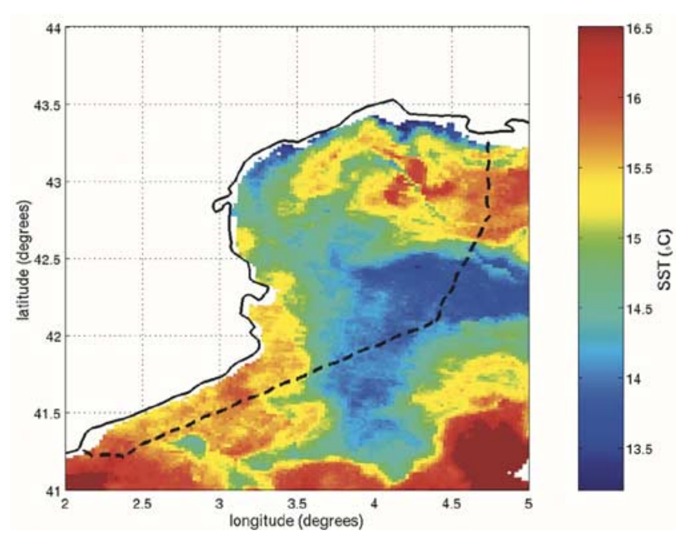

Fig. 3. Composite image of SST retrieved from AVHRR measurements on November 22 and 23, 2001.

Yet, when the AVHRR measurements are colocated with the ship measurements, it appears that the region of low SST moved southwestward by about 0.3° both in longitude and in

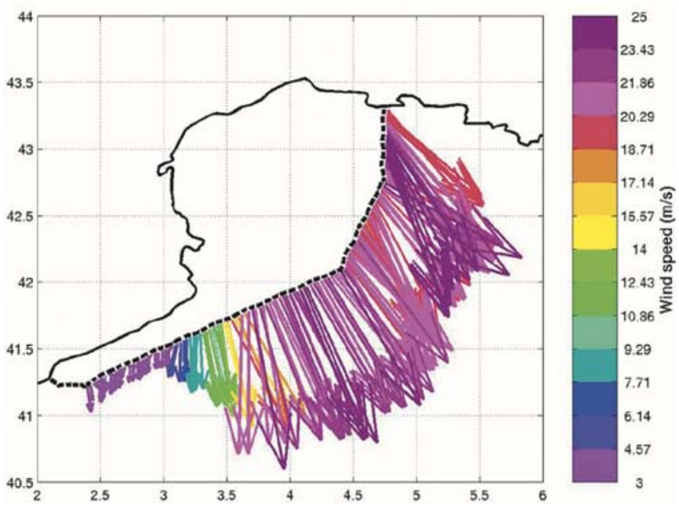

Fig. 4. High-resolution wind speed retrieved from QSCAT measurements along the plane track (dashed line).

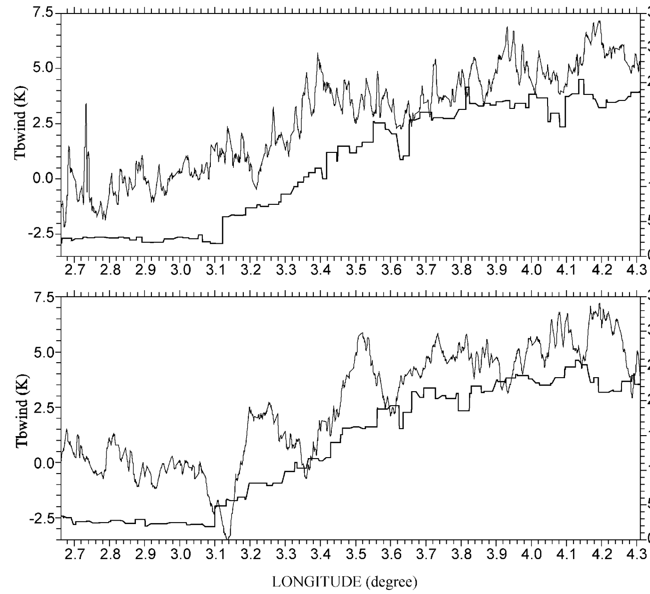

Fig. 5. (Thin line) $T_{\rm bwind}$ and (thick line) U during the first part of the flight. (Top) For 3R antenna. (Bottom) For 2L antenna.

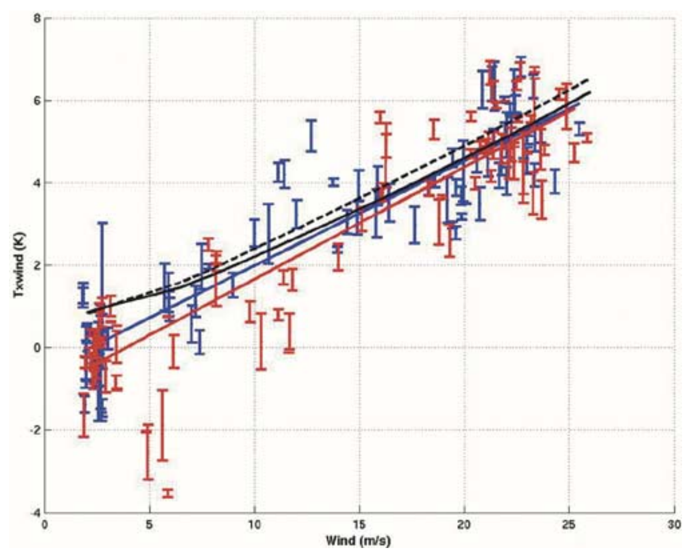

Fig. 6. Measured wind speed dependence for (blue) 3R antenna and (red) 2L antenna. The model results obtained with twice the Durden and Vesecky model spectrum are superimposed (black line). (Dashed line) At incidence 21.5°. (Solid line) At incidence 38.4°.

latitude in five days. When this shift is taken into account, the measurements differ everywhere by less than 0.5°. Considering that, on one hand, the infrared SST has an accuracy of a few tenths of a degree, and on another hand the SST may evolve in five days, we consider this agreement as reasonable. In addition, around 15 °C, the $T_{\rm b}$ sensitivity to temperature is only 0.1 K $(°{\rm C})^{-1}$. Therefore, we use the AVHRR data colocated with the radiometer measurements for SST values, since they were measured approximately at the time of the aircraft flight. The SSS measured in the same zone was rather homogeneous, ranging from 37.7–37.95 psu, with a tendency to increase southward. No correlation with SST was observed, especially no SSS features associated with the observed region of low SST. Unless moving with a varying shelf-slope front, SSS is a slowly time varying quantity due to low air–sea water flux, and it should be relatively stable during five days in this area. In addition, the SSS measured on November 22 at platform *Casablanca* slightly southwest of the plane track (40.72°N 1.36°E) was 38.1 psu in agreement with the ship measurements. Consequently, we consider the SSS to be 37.8 psu all along the flight, since the expected variation of the brightness temperature $(T_{\rm b})$ for such an SSS variation is less than ±0.1 K, a negligible variation compared to the variation due to sea state.

QSCAT passed above the zone at 1734 UT on November 23 during the plane flight. The neutral-stability 10-m height wind velocity was retrieved at 2.5-km pixel resolution by the Brigham Young Microwave Earth Remote Sensing Laboratory using the experimental method described in [9]. The resulting wind colocated along the plane track is shown in Fig. 4. The plane started from Barcelona in a region of light wind (3–4 $\rm m \cdot s^{-1}$) and then crossed a strong gradient to enter a region of strong wind (20–25 $\rm m \cdot s^{-1}$). This gives us a unique opportunity to study the wind speed dependence of $T_{\rm b}$. Though the high-resolution wind measurements used here are somewhat noisier than conventional 25-km QSCAT winds, they are estimated to have rms wind speed errors of less than 2 $\rm m \cdot s^{-1}$. The high-resolution winds provide additional comparison points as well as finer spatial detail. The radiometric measurements analyzed here were made 15–40 min before the satellite pass. Using Taylor's hypothesis (space scale = time scale × wind speed), we estimate that in the meantime the wind structures might move by as much as 7–25 km. This is consistent with the comparison between the ARPEGE meteorological model wind field (0.25° × 0.25°; 6h resolution) at 18h and the QSCAT measurements indicating a westward displacement of the wind speed gradient on the order of 20 km in half an hour. The regions of low and high wind speed being rather homogeneous according to QSCAT, little short-term variability is expected; only the zones of intermediate wind speed might be slightly displaced eastward, and we do not expect that this will have a major impact on the present study.

B. Wind Speed Dependence of T_b

In order to remove most of the dependence of T_b on incidence angle (θ), SST and SSS from the sea state dependence, parameterized through wind speed (U), we split T_b in two terms as in [10]

$$T_\mathrm{b} = T_\mathrm{bflat}\left(\varepsilon(\mathrm{SST},\mathrm{SSS}),\theta\right) + T_\mathrm{bwind}\left(\varepsilon(\mathrm{SST},\mathrm{SSS}),\theta,U,\Phi\right) \quad (1)$$

where ε is the sea water permittivity and Φ the wind direction. We use the two-scale sea surface emissivity model described in [10] and the measured SST, SSS, and θ to compute T_bflat. T_bflat is then subtracted from both the measured and the modeled T_b before comparing modeled and measured T_bwind. The dependence of T_bwind on wind direction, which is expected to be small compared to the measurement accuracy [10], is neglected as well as the dependence of T_bwind on the incidence angle, which is expected to be less than 0.25 K for the range of incidence angles explored by each antenna [11]. For the sea water permittivity, the Klein and Swift [12] parameterization is used. The modeled T_b is corrected for the effects affecting the measured T_b: incidence angle using the plane attitude measurements, antenna pattern effect, atmospheric emission and absorption [13], and galactic and cosmic noise [14]. T_bwind measured by the 3R and 2L antenna beams is plotted together with the wind speed in Fig. 5. Even though the radiometer measurements show large fluctuations at minutes scale, probably due to a superimposed spurious noise suspected to originate from a leakage in the electronic circuits, the increase of T_bwind with wind speed is clear.

The wind speed dependence of the measured T_bwind is shown in Fig. 6. For each QSCAT wind speed measurement colocated with each antenna footprint (the two antennas' footprint centers are 3.6 km apart so that they are colocated with different QSCAT cells), the corresponding $\mathrm{T_b}$ measurements were averaged. The error bars show the standard deviation for each average. The bias between the two beams is due to an imperfect gain calibration. A straight line was fitted by least square fit for each antenna: for the 3R antenna, the slope is $0.252\ \mathrm{K}\cdot\mathrm{m}^{-1}/\mathrm{s}$ (the standard deviation of the measurements with respect to the fit is 0.90 K); for the 2L antenna, the slope is $0.266\ \mathrm{K}\cdot\mathrm{m}^{-1}/\mathrm{s}$ (the standard deviation of the measurements with respect to the fit is 0.93 K). The confidence level at 95% computed with a test of Student is $0.0225\ \mathrm{K}\cdot\mathrm{m}^{-1}/\mathrm{s}$ for the 3R antenna and $0.0233\ \mathrm{K}\cdot\mathrm{m}^{-1}/\mathrm{s}$ for the 2L antenna. The wind speed dependence obtained from the two-scale model at SST 15°, SSS 37.8 psu, and incidence angles 21.5° and 38.4° using twice the Durden and Vesecky spectrum [15] is superimposed on the data: the agreement is quite good, the model slope in this wind speed range being $0.24\ \mathrm{K}\cdot\mathrm{m}^{-1}/\mathrm{s}$. Yet, the data are too noisy to completely validate this model.

In Fig. 7, we plotted the model result for different parameterizations of the sea state with wind speed: Durden and Vesecky spectrum and twice this spectrum, Elfouhaily spectrum [16], Elfouhaily spectrum plus foam (active foam coverage according to [17], and foam emissivity according to [18]). The slope predicted by the Durden and Vesecky spectrum is too low (about $0.12\ \mathrm{km}\cdot\mathrm{s}^{-1}$) to be compatible with the measurements. The plateau predicted below $7\ \mathrm{m}\cdot\mathrm{s}^{-1}$ using the Elfouhaily spectrum is not seen in the data. The slope predicted at moderate wind speed using this same spectrum is about $0.17\ \mathrm{km}\cdot\mathrm{s}^{-1}$ and makes this model rather compatible with our measurements in this wind speed range. The T_b modeled taking into account the foam is by far too large. The foam emissivity model proposed in [18] was derived from measurements made at higher frequencies (above 13.4 GHz) at which the foam effect is expected to be larger and is supposed to be accurate in the range 3–50 GHz. We chose arbitrarily to use this parameterization, since very little is known about the effect of foam at L-band. No particular nonlinear increase in T_b can be seen on our measurements for wind speed larger than 7–10 $\mathrm{m}\cdot\mathrm{s}^{-1}$ (Fig. 6) when wave breaking becomes nonnegligible. This means that the foam effect in L-band, if any, is small. This is compatible with the observations made during the WISE 2001 experiment [19]: the increase in T_b due to foam was 0.1 K for 15-$\mathrm{m}\cdot\mathrm{s}^{-1}$ wind speed at incidence 30° in vertical polarization. Given data scattering, we would not be able to observe such a small increase.

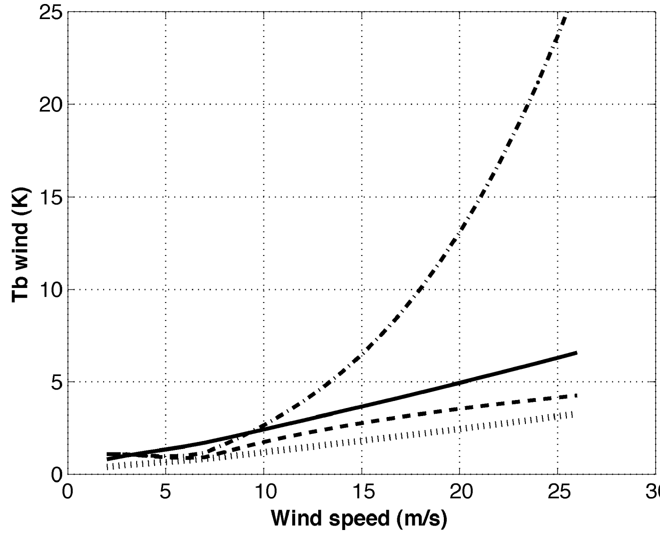

Fig. 7. Modeled wind speed dependence using different spectral parameterizations: (Dotted line) Durden and Vesecky, (dashed line) Elfouhaily, (solid line) twice Durden and Vesecky, (dashed–dotted line) Elfouhaily plus foam.

III. WISE 2001 Field Experiment

This campaign was conducted at Repsol's *Casablanca* oil rig located 40.72°N 1.36°E from October 23 to November 22, 2001. It employed a fully polarimetric L-band radiometer and *in situ* measurements of oceanic and meteorological parameters. A complete description can be found in [20].

Here, we use only the measurements made when the radiometer was pointing at a 44° incidence angle during periods of 1 h. Results obtained at other incidence angles are analyzed in [20]. The T_b measurements were averaged during 15 min. They are compared with wind speed averaged during the same period. Most of the time, we took the wind speed measured onboard a buoy at 2.5-m height except during one week during which it was not available; then, we took wind speed measured at 69-m height. Since in our emissivity model the wind stress is converted into wind speed under a neutral stability assumption, we convert the measured wind speed to equivalent neutral wind speed at 10-m height as follows. The wind stress is deduced under nonneutral conditions from measured air–sea temperature difference, relative humidity, and wind speed using the algorithm described in [21], where the roughness length is the one proposed in [22]. Above the top of the surface layer (defined as ten times the wind speed value), a constant vertical wind profile is used. Then, the wind stress is converted into a wind speed at 10-m height under neutral conditions U assuming a logarithmic vertical profile of the wind. The wind speed dependence of the measured brightness temperature in vertical (T_v) and horizontal (T_h) polarization is shown in Fig. 8 (top). The data points are color coded in SST. A straight line is fitted for wind speed larger than 3 $\mathrm{m \cdot s^{-1}}$. The SST influence is clearly visible: for the same wind speed, the measurements made at low SST are well above those made at higher SST. This is particularly clear for U around 6 $\mathrm{m \cdot s^{-1}}$. These measurements are less noisy than those made at other incidence angles during the same campaign as can be seen in [20]. It might be due to the fact that the measurements at 44° incidence were always performed at the same time and same azimuth, between 9 and 11 UT and pointing westward, while in [20] measurements made at all local times are plotted together as well as measurements made pointing west–north-west and north–northeast. Fig. 9 shows the galactic noise that should enter the radiometer after specular reflection on the sea for measurements performed at 44° and 45°. It was derived from the cosmic background and continuum sources measured during the Stockert survey [23] and from the Hydrogen line emission survey [24]. The signal was convolved by the antenna pattern. It should be multiplied by the reflection coefficient of the sea at these incidence angles: 0.58 and 0.76 for vertical and horizontal polarizations respectively. At 44° incidence, most measurements were made for a galactic noise coming from a quiet region of the galactic sky (galactic noise between 3.3–3.7 K), while at 45° incidence, the antenna sees a signal originating from the galactic plane in the afternoon so that, over one day, the galactic noise varies between 3.3–6.5 K. The measured T_b were corrected for the expected galactic noise, but recent comparisons between galactic noise derived from the above-mentioned surveys and measurements made with radiometers looking at the sky show disagreements up to ± 0.5 K, which origin remains unknown (personal communication, Y. Kerr). Hence, the quality of the galactic noise corrections that were applied to WISE measurements is possibly dependent on the region of the galactic sky (i.e., on the local time of the radiometric measurements).

Fig. 8 (bottom) shows the same plot for T_bwind. The scatter of the points is now random. The standard deviation of the points with respect to the fit is decreased by about 0.1 K, from 0.153 to 0.036 K in vertical polarization and from 0.431 to 0.333 K in horizontal polarization. In Fig. 8, it can be clearly seen that T_bwind abruptly decreases for wind speed lower than 3 $\mathrm{m \cdot s^{-1}}$. This behavior was observed at 2.65 GHz by [25] during a flight above Chesapeake Bay. It was not observed during the EuroSTARRS flight, probably because both the T_b and the wind speed measurements were noisy; it is known that the scatterometer measurements are very inaccurate below 3 $\mathrm{m \cdot s^{-1}}$. The slope of the fit between 3–18 $\mathrm{m \cdot s^{-1}}$ is 0.014 $\mathrm{K \cdot m^{-1}/s}$ in vertical polarization and 0.195 $\mathrm{K \cdot m^{-1}/s}$ in horizontal polarization, different from what is found at 45° incidence angle in [20]. This might be due to the inaccuracy generated by more noisy data at 45°, as discussed above. Also, the azimuth of the measurements is not the same, and different sea states are observed in different directions due to wave reflection on the platform as discussed in [20]. The

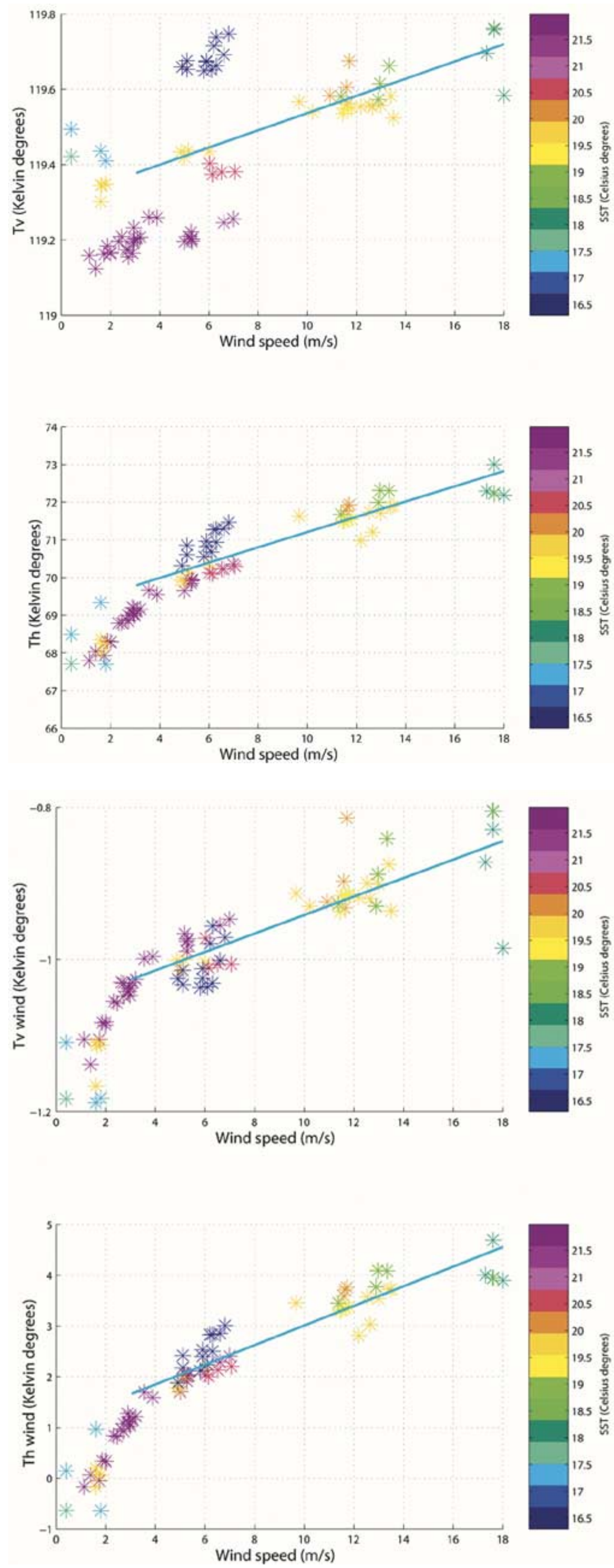

Fig. 8. Wind speed dependence in (top) vertical and (bottom) horizontal polarizations measured at 44° incidence angle during WISE 2001 of brightness temperature and T_bwind.

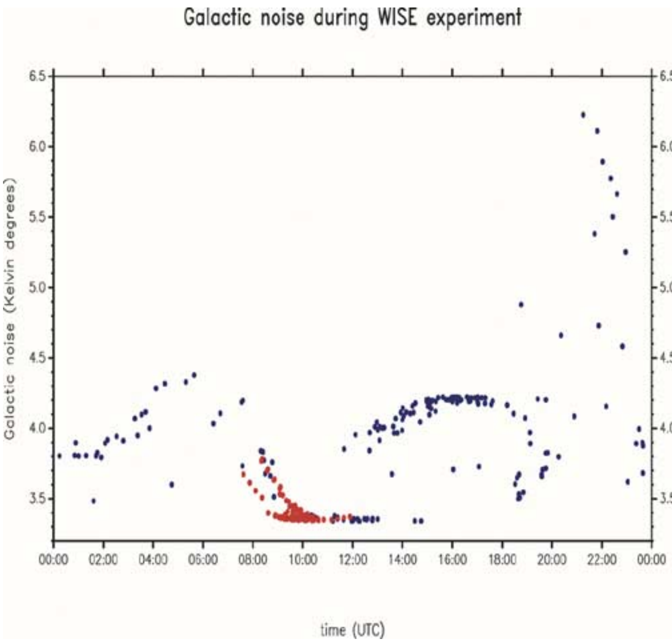

Fig. 9. Galactic noise seen by the radiometer during measurements at (red) incidence 44° and (blue) at 45° (blue).

wind speed dependence found for the two-scale sea surface emissivity model described in [10] above 3 m · s^{-1} using the different parameterizations of the sea spectrum is 0.087, 0.129, and 0.173 K · m^{-1}/s in vertical polarization and 0.158, 0.213, and 0.315 K · m^{-1}/s in horizontal polarization for the Durden and Vesecky, the Elfouhaily, and twice the Durden and Vesecky spectra, respectively. In vertical polarization, the measurements have wind speed dependence weaker than any of the model result. In horizontal polarization, it lies between Durden and Vesecky and Elfouhaily. This disagreement between model and data might come from a modification of part of the wave spectrum due to the presence of the platform, especially by creating reflected waves. In addition, it was observed during WISE 2000 that waves reflected by the platform affect the amount of foam: the foam coverage observed north of the platform was lower than the one observed west by one order of magnitude [6].

IV. Discussion and Conclusion

We studied measurements from two campaigns to improve our knowledge of the wind sensitivity of brightness temperature at L-band. During EuroSTARRS, very strong winds were encountered. It enables us to compare observations to a two-scale emissivity model for T_{v} at moderate and high wind speed. Within the accuracy of the measurements, the agreement between data and model is good when modeling the sea state with twice the Durden and Vesecky spectrum. When using the Elfouhaily spectrum, for winds below 7 m · s^{-1}, the data are in disagreement with the model, while they are not incompatible at higher wind speed taking into account the noise of the measurements. It is also shown that the effect of foam on T_{v} cannot be large. During the WISE 2001 campaign, low noise measurements at incidence 44° were performed at low and moderate wind speed. It enables us to check the validity of studying the wind speed dependence on T_{bwind} rather than on T_{b}. We could see an abrupt decrease of T_{bwind} for wind speed lower than 3 m · s^{-1}. The wind speed dependence of T_{vwind} above 3 m · s^{-1} is much less than what was observed during EuroSTARRS. Even though the model predicts a decrease with incidence angle for θ larger than 40°, this result cannot be reconciled with the model. It might come from a distortion of the sea state during WISE 2001 due to the presence of the platform. Even though more measurements are needed to completely validate an L-band emissivity model, these results are encouraging.

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