SMOS Satellite L-band Radiometer: a new Capability for Ocean Surface Remote Sensing in Hurricanes

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• Context
• Review of our understanding of L-band Radiometry at High Winds
• IGOR Hurricane Case Study
• Perspective
Figure 1: Photograph of the sea surface during a hurricane (Beaufort Force 12) taken from a NOAA “Hurricane Hunter” aircraft (Black et al., 1986).
A complex distribution of two-phase oceanic phenomena

Fig. 1. Classifications of oceanic dispersed media for remote sensing.
Figure 9: Sea State 2D wave spectra measured by an airborne Scanning Radar Altimeter around the eye of hurricane Yvan (2004). Contours of the wind field structure from H*WIND analysis are provided as well (Black et al., 2007).
Extreme Sea State conditions

(a) $H_{\text{rms}}$ [m]

(b) $T_{\text{max}}$ [s]

Days in September 2010
Varying foam-layer thicknesses

**Figure 8.** Significant surface wave height and bubble cloud depth measured by nine SOLO floats during hurricane Frances in 2004 and wind speed at the float location from H*WIND analysis. Time axis is hours from time of maximum wind at each float (Black et al., 2007).
Increase of the microwave ocean emissivity with wind speed ⇔ foam effect

This information can be used to retrieve the surface wind speed in Hurricanes:

Principle of the Step Frequency Microwave Radiometer (SFMR) :

NOAA’s primary airborne sensor for measuring Tropical Cyclone surface wind speeds since 30 year (Ulhorn et al., 2003, 2007).
High winds in Hurricanes are very often associated with High rain rates.

Rain Anatomy in a hurricane:

- Primary eyewall
- Secondary eyewall
- Distant rainbands
- Inner core
- Environment

Rain rate [mm/h]

S. Shen 2007
Limitations of current satellite MW observing systems operating at frequencies ≥ C-band

C-band passive/active data are strongly affected by rain

C-band active saturates at high winds

Figure 5. Normalized radar cross section (NRCS) versus centerline (0.3 m height) wind speed in the tank. Note that $U_{10}$ is approximately $1.5U_{0.3}$. 
Signatures of Tropical Cyclones in 2010 SMOS data

HURRICANE DANIELLE

HURRICANE EARL
Signatures of Tropical Cyclones in 2010 SMOS data

HURRICANE IGOR

TROPICAL STORM JULIA
Current Understanding of
L-band radiometry in High winds:
A review:
At 37 psu salt water the foam-induced emissivity increase is 0.007 per mm of foam thickness (extrapolated to nadir), increasing with increasing incidence angles at vertical polarization, and decreasing with increasing incidence angles at horizontal polarization.

\[
\varepsilon_{\text{Total}}^{h,v} (\theta) = F \cdot \varepsilon_{\text{Foam}}^{h,v} (\theta) + [1 - F] \cdot \varepsilon_{\text{Water}}^{h,v} (\theta)
\]

Foam emissivity Modeling

Bordonskiy et al.
Dombrovskiy and Raizer

“Microwave model of a two-phase medium at the ocean surface”,
Izvestiya, Atmospheric and Oceanic Physics,

\[
R_p(\theta_i) = \frac{R_p^{01}(\theta_i)e^{-j2\psi} + R_p^{12}(\theta_i)}{e^{-j2\psi} + R_p^{01}(\theta_i)R_p^{12}(\theta_i)}
\]

Reul, 2002

effective dielectric constant \( \varepsilon_N \alpha \)

\[
\varepsilon_N \alpha = \frac{1 + \frac{8}{3} \pi N \cdot \alpha(r)}{1 - \frac{4}{3} \pi N \cdot \alpha(r)}
\]

where

\[
N \cdot \alpha(r) = \frac{\kappa}{4} \int \alpha(r)p_f(r)dr
\]

dipole approximation model

At L-band

the contribution of multipole moment occur for bubbles’ radius

on the order of 10 cm.
Comparison Foam-layer emissivity model at L-band and FROG data

At H-polarization the agreement is excellent,
At V-polarization, the measured values show a larger variation with incidence angle

Coverage and thickness weighted Foam-layer emissivity model

The contribution of foam formations to sea surface brightness temperature as function of wind speed $U$ is given by:

$$T_{Bf}(\theta, p, f, U) = \int F(U, \delta) \cdot T_s \cdot e^{typ}_{Bf}(\theta, p, f, \delta) d\delta$$

Where

• $f$, $p$ and $\theta$ are the receiving electromagnetic frequency, polarization and incidence angle of the radiometer respectively,

• $F(U, \delta)$ is the fraction of sea surface area covered by whitecaps with thickness $\delta$ at $U$,

• $T_s$ is the physical temperature of foam, usually assumed the same as the bulk sea surface temperature and,

• $e^{typ}_{Bf}$ is the emissivity of typical sea foam-layer.

Coverage and thickness weighted Foam-layer emissivity model

\[ e_B = e_{\text{spec}} + [\Delta e_{\text{rough}} + \Delta e_{\text{whitecaps}}] \]

\textit{wind-induced}

H-Pol, \( \theta_i = 25^\circ \)
Linear increase of Tb with wind
Up to 28 m/s
Weak incidence angle dependence
At high winds

Fig. 13. V and H brightness temperatures taken at a 45° incidence angle from the star pattern (blue), inbound (red), and outbound (black) tracks on March 2, 2008, are plotted versus the wind speed derived from the POLSARF measurements. All brightness temperature measurements have been translated to a 45° incidence angle and corrected for galactic radiation.

According to PALS sensitivity ~0.35K/m/s for the First Stokes parameter/2

C-band TB~3 times more sensitive to wind speed than L-band

SMOS L-band model overestimates the Tb increase with wind for U>12 m/s
Because of the small ratio of raindrop size to the SMOS electromagnetic wavelength (~21 cm), scattering by rain is almost negligible at L-band, even at the high rain rates experienced in hurricanes. Rain impact at 1.4 GHz can be approximated entirely by absorption and emission (Rayleigh scattering approximation valid). Generally two order of magnitude smaller at L-band (1.4 GHz) than at C-band (5-7 GHz).
Potential rain impact at L-band

At L-band, increase in $T_b$ due to rain is simply proportional to the total content of liquid water.

$$\Delta T_{B,liq} = 2(1 - E)\bar{T}_{liq} \bar{a}_{ray} L \text{ sec } \theta$$

$E$: surface emissivity

$\bar{T}_{liq}$: average temperature of the rain cloud

$\bar{a}_{ray}$: Rayleigh coefficient at temperature $\bar{T}_{liq}$

$L$ is the total content of liquid water in the field of view

Assuming a tropical rain layer thickness of 3 km, the model predicts an increase in the first Stokes parameter due to rain of

$\Delta T_{B,liq} = ~0.2 \text{ K at a rain rate of 10 mm.hr}^{-1}$

$~0.35 \text{ K at a rain rate of 30 mm.hr}^{-1}$

(first Stokes parameter/2)
In very high rain rates \( \sim 90 \text{ mm/h} \) => potential significative impact

\[ \Delta T_B,\text{liq} = 4 \text{ K for the first Stokes parameter/2} \]
Analysis of SMOS signature over Category 4 Hurricane IGOR
Collection of Hurricane Igor data:

• SMOS L1B data corrected for all contributions except roughness (sss=clim)

• National Hurricane Center Best Track data:
  => track; max winds, radius at 34, 50 and 64 knots

• AOML Hurricane research division
  => H*WIND observation analysis winds
  => SFMR data
• NOAA/NWS/NCEP North Atlantic Hurricane Wind Wave forecasting system (NAH):
  => Wave parameters

• NOAA/Geophysical Fluid Dynamic Laboratory (GFDL) hurricane model winds
• ECMWF
• ASCAT
• SSM/I, WindSAt
Geophysical Model function: $T_b = f(\text{wind speed})$

- Change of sensitivity at Hurricane wind Force (>33 m/s)
- Weak Incidence Angle dependence
- Very consistent With PALS
Geophysical Model function: \( T_b = f(\text{wind speed}) \)

\[
\Delta I = \frac{\Delta(T_B + T_r)}{2} = 0.35 \ U_{10} \cdot 1.3 \quad U_{10} \leq 33 \ \text{m.s}^{-1}
\]
\[
= 0.75 \ U_{10} \cdot 14.5 \quad U_{10} \geq 33 \ \text{m.s}^{-1}
\]
Wind field Structure from SMOS

Radius of wind speed larger than 34, 50 and 64 knots
SMOS clearly outperform ASCAT in that case.
Comparison at SFMR transects

(a) Wind speed - Rain rate

(b) SFMR C-band $T_B$ [K] vs SMOS L-band $\Delta T_B$ [K]
windSat rain Rate exactly at the same time than SMOS

No clear signature correlated with highest rain rates here
Perspectives
Figure 11: Map showing the tracks of all Tropical cyclones which formed worldwide from 1985 to 2005 (NASA). In Red: area for which Radio Frequency Interference strongly contaminate SMOS data, in orange, zones for which potentially strong land contamination is expected. In green: potential test zones.
Salinity and Wind retrieval from L-band sensors: a promising synergy for Hurricane study
Fresh water wakes behind hurricanes

SSS wake?

No clear signal