Effect of sea surface temperature on sea surface brightness temperature measured by L-band microwave radiometers

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Abstract. The effect of sea surface temperature (SST) on sea surface brightness temperature measured by L-band microwave radiometers is estimated in this paper. We found systematic SST dependence in Aquarius radar backscatter $\sigma_0$, radiometer excess emissivity $\Delta e$ as well as sea surface excess brightness temperature $\Delta T_b$. The influences of SST on $\sigma_0$, $\Delta e$ and $\Delta T_b$ in cold water are much more bigger than that in warm water. The precision of the corrected measured flat sea surface bright temperature is improved significantly after correcting with SST.

1. Introduction

Aquarius is a sea surface salinity (SSS) satellite, which carries both L-band microwave radiometer and L-band microwave scatterometer. L-band microwave radiometer is an effective means to obtain SSS by measuring sea surface bright temperature. The measurement principle is based on the response of the L-band bright temperature to seawater’s dielectric constant determined by SSS and sea surface temperature (SST) [1, 2]. It is difficult to retrieve SSS with the measurement of L-band radiometry; therefore, the precise bright temperature corrections are necessary to obtain accurate SSS retrieval [3]. One of the major drivers that “warm” bright temperature is the change of the ocean surface emission due to sea surface roughness, which can be measured by scatterometer and expressed by radar backscatter ($\sigma_0$) [4]. Correction models for most satellite radar do not parameterize bright temperature on SST appropriately. However, Vandemark et al. [5] affirmed that SST is the dominant control in the Ka-band (35 GHz) radar altimeter reflectivity. The systematic improvement was found in the Ka-band wind speed retrieval after SST effect correction. But there remains a question whether the same performance will be found at L-band frequencies. Meissner et al. [6] provided a simple estimate of the sensitive of bright temperature to SST based on physics of the electromagnetic microwave emission of a flat ocean surface at the L-band. The results showed that the sensitivity of bright temperature for flat ocean surface to SST will increase when the water becomes colder. Tang et al. [7] investigated the effect of SST on L-band microwave measurements and its implication on SSS retrieval. They found that radiometer excess emissivity and the accuracy of SSS depend significantly on SST.

This paper mainly aims at providing a further study of the effect of SST on L-band bright temperature of a rough ocean surface and its correction.
2. SST influence on bright temperature

The bright temperature measured from sea surface $T_{b_{\text{meas}}}$ can be decomposed into two parts. One part is the specular sea surface bright temperature ($T_{b_0}$) and another part is the bright temperature increment caused by sea surface roughness ($\Delta T_{b}$). The specular sea surface bright temperature $T_{b_0}$ can be expressed as:

$$T_{b_0} = e_0(T, S) \cdot T$$  \hspace{1cm} (1)

Here, $e_0$ is the specular sea surface emissivity, which depends on SST ($T$) and SSS ($S$). It can be calculated by the Fresnel equations of specular reflection and determined by the model of the dielectric constant of sea water with ancillary SSS and SST fields as the inputs [8, 9]. Then, the bright temperature increment caused by sea surface roughness $\Delta T_{b}$ can be expressed as follows:

$$\Delta T_{b} = T_{b_{\text{meas}}} - T_{b_0}$$  \hspace{1cm} (2)

The $\Delta T_{b}$ is mainly caused by sea surface wind, which most correction models have considered. But the change of SST will result in different $\Delta T_{b}$, which may also be a non-negligible factor. To estimate the influence of SST on bright temperature, the Aquarius L2 bright temperature and radar backscatter measurements from September 2011 to August 2012 were used in this paper. The co-located ancillary SSS fields are from HYbrid Coordinate Ocean Model (HYCOM), and the ancillary SST and wind fields are from National Centers of Environmental Prediction (NCEP). The variations of $\Delta T_{b}$ with SST change are shown in Fig. 1.

Fig. 1 indicates that, the overall $\Delta T_{b}$ value is slightly bigger for H-polarization than for V-polarization, and it is almost insensitive to incident angle for V-polarization whereas slightly increases with increasing incidence angles for H-polarization. As the water becomes colder, the bright temperature increment $\Delta T_{b}$ increases for both polarizations and all horns. Although the $\Delta T_{b}$ values are different, the volumes of change in $\Delta T_{b}$ are almost the same for all the case displayed. The volumes of change in $\Delta T_{b}$ is approximately 0.7 - 0.9 K, as the SST decreases from 30 °C to 0 °C. It can be seen from the error bar that the uncertainty of $\Delta T_{b}$ for $T = 0$ °C is about 1.2 K which is about 0.5 K bigger than that for $T = 30$ °C. The uncertainty in the surface $\Delta T_{b}$ (in Kelvin) translating into an SSS uncertainty (in psu) is roughly 1:2 which means that the 0.5 K $\Delta T_{b}$ uncertainty will lead to 1.0 psu SSS uncertainty. However, goal of Aquarius is to provide monthly global SSS fields with a root mean squared difference (RMSD) of 0.2 psu, which reminds us that the influence of SST especially low SST on bright temperature shouldn't be ignored.
3. SST effect on bright temperature correction

To reduce the influence of SST on $T_b$, it is corrected for the $T_b$ caused by sea surface roughness. Sea surface roughness is characterized by Geophysical Model Function (GMF) for radar backscatter ($\sigma_0$) and for radiometer excess emissivity ($\Delta e = \Delta T_b/T$). $\sigma_0$ and $\Delta e$ were grouped into bins with step size of 1 °C in SST, 1 m · s$^{-1}$ in wind speed, and 10° in wind direction. The data in each bin were averaged to represent the expected microwave response at the given SST, wind speed and wind direction.

Fig. 2 shows the influence of SST on $\sigma_0$ normalized by the data at common surface temperature 17°C, i.e. $\beta = \sigma_0(W, T)/\sigma_0(W, 17°C)$, here $W$ is wind speed. It can be seen that $\sigma_0$s are much bigger in cold water than in warm water when wind speed is lower than 5 m · s$^{-1}$. This phenomenon is particularly obvious for HH polarization but have no dependence on incidence angles. When the wind is between 10 m · s$^{-1}$ and 15 m · s$^{-1}$, $\sigma_0$s in cold water becomes slightly smaller than that in warm water, but both of them are bigger than 1.
Fig. 2. Dependence of radar $\sigma_0$ for VV and HH polarizations on ocean surface wind speed and SST for three horns at incidence angle 28.7 °, 37.8 ° and 45.6 ° (up to down).

The influence of SST on the excess emissivity $\Delta e$ is illustrated in terms of its difference with data at common surface temperature 17 °C, i.e. $\delta e = \Delta e(W, T) - \Delta e(W, 17^\circ C)$, as shown in Fig. 3. When SST is smaller than 5 °C, $\Delta e$ increases as wind speed becomes smaller. Meanwhile, $\Delta e$ increases with decreasing SST at most wind speed, and $\Delta e$ is bigger for H polarization than for V polarization when SST smaller than 10 °C. This suggests that the correction without considering the SST effect would underestimate the roughness for cold water.
Fig. 3. Dependence of radar $\Delta e$ for V and H polarizations on ocean surface wind speed and SST for three horns at incidence angle 28.7 °, 37.8 ° and 45.6 ° (up to down).

We implemented an empirical SST correction using the $\beta$ & $\delta e$ as lookup tables and combined with wind/wave induced roughness model. Then the radar backscatter $\sigma_0$ can be expanded into a Fourier series of even harmonic functions in the relative wind direction $\varphi_r$ after correction with $\beta$[10]. We keep terms up to second order:

$$\sigma_{0,p} = \beta_p(T,W) \cdot [B_{0,p}(W) + B_{1,p}(W) \cdot \cos(\varphi_r) + B_{2,p}(W) \cdot \cos(2 \cdot \varphi_r)]$$  \hspace{1cm} (3)

Here, $p = VV, HH, VH, HV$ is the polarization and $B_{k,p}, k = 0, 1, 2$ is the harmonic coefficient. We regress the $\sigma_0$ measurements to the set of even harmonic basis functions ($1; \cos(\varphi_r); \cos(2 \cdot \varphi_r)$) in each of the 1 m/s wide wind speed bins. The results for $B_{k,p}, k = 0, 1, 2$ and $p = VV, HH, VH, HV$ in each bin are then fitted by a fifth-order polynomial in $W$:

$$B_{k,p}(W) = \sum_{i=0}^{5} b_{klp} \cdot W^i$$ \hspace{1cm} (4)

Here, $b_{klp}$ is the fit coefficient.

The model function for the wind-induced emissivity $\Delta e_0$ after correction with $\delta e$ is also an even second-order harmonic expansion:

$$\Delta e_{0,p} = \delta e_p(T,W) + [A_{0,p}(W) + A_{1,p}(W) \cdot \cos(\varphi_r) + A_{2,p}(W) \cdot \cos(2 \cdot \varphi_r)]$$  \hspace{1cm} (5)

Here, $p = V, H$ is the polarization and $A_{k,p}, k = 0, 1, 2$ is the harmonic coefficient. We regress the $\Delta e_0$ measurements to the set of even harmonic basis functions ($1; \cos(\varphi_r); \cos(2 \cdot \varphi_r)$) in each of the 1 m/s wide wind speed bins. The results for $A_{k,p}, k = 0, 1, 2$ and $p = V, H$ in each bin are then fitted by a fifth-order polynomial in $W$: 
A_{k,p}(W) = \sum_{i=0}^{5} a_{k,i,p} \cdot W^i \quad (6)

Here, $a_{k,i,p}$ is the fit coefficient.

Then the total roughness induced emissivity $\Delta e_{\text{rough}}$ can be formed as follows:

$$\Delta e_{\text{rough}} = \Delta e_0(T, W) + \Delta e_1(W, \sigma'_{0,vv}) \quad (7)$$

Here, $\Delta e_1(W, \sigma'_{0,vv})$ is a two-dimensional lookup table that depends on wind speed and $\sigma'_{0,vv}$.

$\sigma'_{0,vv}$ is the measurement of the VV-pol radar cross section after removing the wind direction signal, which can be expressed as follows:

$$\sigma'_{0,vv} = \sigma_{0,vv}^{\text{meas}} - \beta_p(T, W) \cdot \left[B_1,p(W) \cdot \cos(\varphi_T) + B_2,p(W) \cdot \cos(2 \cdot \varphi_T)\right] \quad (8)$$

Here, $\sigma_{0,vv}^{\text{meas}}$ is the measurement of the VV-pol radar cross section.

Finally, the measured flat sea surface bright temperature $T_{b0,\text{meas}}$ can be calculated as follows:

$$T_{b0,\text{meas}} = T_{b\text{meas}} - \Delta e_{\text{rough}} \cdot T \quad (9)$$

Fig. 4 shows the probability distribution of the difference between the measured and actual flat sea surface bright temperature ($T_{b0,\text{meas}} - T_{b0}$). The probability of measured flat sea surface bright temperature minus actual flat sea surface bright temperature with SST correction shows a larger cluster of values at or near zero than that without SST correction. The percentages of the difference after SST correction that lie in the difference range from $-0.2$ K to $0.2$ K is 60.86%, whereas that for the difference without SST correction is only 52.18%. The number of outliers, defined here as the differences bigger than 0.6 K, is about 1.95% for the difference with SST correction, while it is 5.19% for the difference without SST correction. The root mean square (RMS) values for the difference with and without SST correction are 0.24 K and 0.30 K, respectively. It shows that there is a significant improvement in bright temperature correction after correcting with SST.

**Fig. 4.** Probability distribution of the difference between the measured and actual flat sea surface bright temperature.

**4. Conclusion**

Effect of SST on bright temperature is estimated in this paper. As the water becomes colder, the bright temperature increment $\Delta Tb$ increases for both polarizations and all horns. When wind speed is smaller than 5 m $\cdot$ s$^{-1}$, both $\sigma_0$s and $\Delta$es are much bigger in cold water than in warm water, which shows that SST especially low SST has serious influence on bright temperature. After correcting with SST, the
precision of the corrected measured flat sea surface bright temperature is improved significantly. In a word, SST has a significant influence on bright temperature and should not be ignored in the progress of correcting bright temperature caused by sea surface roughness.

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