Ocean Wind Speed Retrieval Algorithm using the frequency 36GHz Vertical/Horizontal and 6GHz Horizontal Data of the Advanced Microwave Scanning Radiometer (AMSR)

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Abstract
An algorithm of retrieving wind speed from the Advanced Microwave Scanning Radiometer (AMSR) was developed by combining data of AMSR and the scatterometer SeaWinds, both aboard the Advanced Earth Observation Satellite-II which operated during seven months in 2003. Data combining aided the AMSR algorithm development in following two evaluations: one is the atmospheric effect, and the other is the sea surface temperature effect, while the SeaWinds wind data are almost free from these effects. The developed algorithm was examined by comparing the AMSR wind speed with ocean buoy’s one. The bias of AMSR minus buoy wind speed is –0.008m/s, and root mean square of differences is 0.954m/s, in which the number of collocated AMSR and buoy data is about 3200 during seven months.

Keywords: AMSR, SeaWinds, ADEOS-II, wind speed.

Introduction
The Advanced Earth Observation Satellite-II (ADEOS-II) launched by the Japan Aerospace Exploration Agency (JAXA) provided combination data observed by passive and active sensors during seven month since April 2003: the passive sensor is the Advanced Microwave Scanning Radiometer (AMSR) and the active one is the SeaWinds. The AMSR is an eight frequency, forward-looking, conically scanning radiometer developed by the JAXA [Kawanishi et al., 2003]. The AMSR antenna rotates at 40rpm with a constant incidence angle of 55 degree, and 196 pixels data are collected per one rotation. The SeaWinds is a scatterometer developed by the National Aeronautics and Space Administration (NASA), which measures wind speed and direction over ocean surface [Liu, 2002].

Algorithms of retrieving ocean wind speed from passive microwave radiometers such as AMSR should deal with two big problems: one is the atmospheric correction and the other is the sea surface temperature (SST) dependency. The latter comes from the fact that the ocean microwave emission depends on SST. On the other hand, wind algorithms for scatterometer such as SeaWinds are almost free from those two problems [Liu, 2002]. Further more, the SeaWinds provides the information on the wind direction, of which retrieval is very difficult for AMSR. Therefore, the combination of AMSR and SeaWinds aids in developing an accurate ocean wind speed.
algorithm for AMSR. The combination of AMSR-type microwave radiometer and scatterometer on the ADEOS-II is the second opportunity; the first one was on the Seasat launched by NASA in 1978. We have not yet obtained the next opportunity on a budget-approved satellite.

**Algorithm**

The AMSR frequencies are 6, 10, 18, 23, 36, 50, 52, and 89GHz, and both polarizations (vertical and horizontal, hereafter V/H) are available for six frequencies, except than for 50 and 52GHz in which only V is available. Since it is advantage to use both polarizations at the same frequency in retrieving ocean wind speed, the channels 50V and 52V are not considered. In previous papers [Shibata, 2004; Shibata, 2006], the brightness temperature (Tb) of two frequencies 6 and 10GHz with two polarizations (T$_{6V}$*/T$_{6H}$* and T$_{10V}$*/T$_{10H}$*) were reported in relation with ocean wind. T$_{6V}$* is the AMSR T$_{6V}$ corrected for atmospheric contamination and SST effects. The same applies to T$_{6H}$*/T$_{10V}$*/T$_{10H}$*. Atmospheric contamination is calculated by using T$_{23V}$ and T$_{36V}$ (see Fig. 1 in [Shibata, 2004]), and rainy areas are masked. As shown in Figure 2 of [Shibata, 2004], T$_{6V}$* is constant under weak wind condition (≤ 6m/s), and it increases gradually above its speed. T$_{6H}$* increases even under weak wind condition, and its increment is larger than T$_{6V}$* in all wind speeds. An anisotropic feature depending on a relative wind direction (RWD), the angle made by two directions of AMSR viewing and wind direction, is found in both polarizations. T$_{6V}$* is maximum in upwind and minimum in downwind direction; T$_{6H}$* is maximum in crosswind and minimum in both up and downwind directions (see Fig. 2 of [Shibata, 2004]). The behavior of 10GHz is almost similar to 6GHz at both polarizations, and its sensitivity to wind speed is slightly greater than 6GHz [Shibata, 2007].

![Figure 1 - Definition of S36. Calculated T$_{36V}$ (vertical axis) and T$_{36H}$ (horizontal axis) are plotted under two ocean conditions: calm one (OA) and roughened one by wind (WA). The parameter representing wind speed, S36, is defined as a horizontal length between OA and WA.](image-url)
Figure 2 - Anisotropic features of S89, S36, S23, and S18 versus RWD. In each plot, ten cases of SeaWinds wind speed from 1 to 19m/s with 2m/s intervals are shown. RWD is defined as the angle made between the SeaWinds wind direction and AMSR viewing direction.

Tb at 36GHz has been computed at a satellite height using the microwave transfer model, of which details were already described in Shibata [1994] and Shibata [2004]. The atmospheric part of this model deals with only absorption processes by water vapor, oxygen, and cloud liquid water, and does not deal with a scattering process by raindrops. The reflection on a calm ocean surface was described by the Fresnel formula, in which the complex dielectric constant of ocean water was obtained from [Klein and Swift, 1977]. The model uses the daily aerological data of about sixteen Japanese observation sites in one year for intervening atmospheric parameters. Figure 1 reports the calculated $T_{36V}$ (ordinate) versus $T_{36H}$ (abscissa) both in unit Kelvin. The dots represent averaged values of $T_{36H}$ corresponding to $T_{36V}$ with 1K interval. In these calculations, a total amount of water vapor varies from 5 to 60Kg/m$^2$, and liquid water content takes two values of 0 and 0.4Kg/m$^2$. A line shown by OA is a regression line of these data. The line OA represents the calm ocean surface condition; the line WA the roughened ocean surface by wind, in which the emissivity of V increases by 0.01, and the one of H increases by 0.1. Two lines OA and WA intersect at the point A. For another changes of surface emissivity, regression lines also intersect at the point A. Tb of the point A is about 300K for both polarizations, which may represent the intervening atmospheric temperature in a lower level. Under an infinite unopaque condition, Tb may approach toward the atmospheric temperature in the lower level, regardless of ocean surface condition.

A parameter representing ocean wind is defined by a horizontal length between OA and WA, as expressed by S36 in Figure 1, and written as in eq.[1].
The coefficient $b$ is constant, whereas $a$ and $c$ depend on SST. In eq.[1], $f$ means the atmospheric correction and represents the convergence made by two lines $OA$ and $WA$. $T_b$ difference of $T_{36V}$ between $O$ and $A$ is about 100K, and $f$ diminishes when $T_{36V}$ approaching 300K in eq.[2]. In the previous paper [Shibata, 2004], $f$ was reported as 0.004, but the value of 0.01 is more accurate because of discussions about the intersection point $A$. In eq.[1], $t$ is an offset, which will be explained later. The position of point $O$ shifts in accordance with SST change, and values of $a$ and $c$ depend on SST. Values of $a$ and $c$ can be determined by comparing $S36$ with the SeaWinds wind speed. It is ideal that these values be determined against 0m/s of SeaWinds wind speed, and $t=0$ in this case. But, such a case is very rare, and collocated number is not enough for comparison. Therefore, collocated data are obtained at the SeaWinds speed of 5m/s (i.e., in a range from 4.5 to 5.5m/s), and $t$ is set as 4.5 empirically. Table 1 lists values of $a$ and $c$ at seven SSTs from 0 to 30ºC with 5ºC intervals.

Here, SST is collected from the Reynolds SST with a weekly analysis [Reynolds and Smith, 1994]. In collecting collocated data, rainy areas were masked using the same technique in deriving $T_{6V}$. The technique of using eq.[1] can be also applied to other frequencies of 18, 23, and 89GHz, though their SST dependencies are not listed. Hereafter, those parameters of other frequencies are called as $S18$, $S23$, and $S89$, respectively.

Table 1 - Values of $a$ and $c$ against seven SSTs.

| SST | $a$   | $c$   |
|-----|-------|-------|
| 0 °C | 2.23  | 132.0 |
| 5   | 2.20  | 132.2 |
| 10  | 2.14  | 131.7 |
| 15  | 2.06  | 131.2 |
| 20  | 2.07  | 128.9 |
| 25  | 2.07  | 126.7 |
| 30  | 2.06  | 124.2 |

$S36$ et al. have also the anisotropic features depending on RWD, and their dependencies can be determined by comparing these parameters with the SeaWinds wind speed and direction. In Figure 2, $S89$, $S36$, $S23$, and $S18$ are shown against RWD and to ten cases of SeaWinds wind speed from 1 to 19m/s with 2m/s intervals. It is clear that the sensitivity to wind speed becomes larger with the frequency increasing, i.e., $S89$ largest, $S36$ middle, $S23$ and $S18$ smallest. But, the behavior of $S89$ seems to be noisier than other frequencies, which may be attributed to atmospheric contamination at higher frequency. Therefore, $S36$ is the best parameter in retrieving wind speed. $S36$ is almost constant to RWD in weak wind speed less than 5-7m/s. For wind speeds over this value, $S36$ has an anisotropic feature, becoming
the minimum in upwind, and the maximum in downwind direction. As mentioned above, $T_{6V}$ takes the maximum in upwind, and the minimum in downwind direction. Assuming that this feature of $T_{6V}$ keeps similarly at $T_{36V}$, $S36$ takes the minimum in upwind direction, because $a \times T_{36V}$ is dominant in eq.[1] ($a$ is almost equal to 2). As for the maximum value, $S36$ takes the maximum in downwind direction, and $S18$ takes the maximum in directions between cross and downwind (the feature of $S23$ is middle between $S36$ and $S18$).

The anisotropic feature of $S36$ should be corrected before converting $S36$ to wind speed, because the converted wind speed has the anisotropic feature. Figure 3 depicts a relation between $S36$ and $T_{6H\ast}$ for three cases of RWDs (up, cross, and downwind) and ten cases of wind speeds (from 1 to 19m/s with 2m/s intervals) are shown. As mentioned previously, $S36$ is maximum in down and minimum in upwind direction. Also, $T_{6H\ast}$ is maximum in cross and minimum in up and downwind directions. The anisotropic correction means that $S36$ in both up and downwind directions are adjusted to $S36$ in crosswind direction, following slopes in Figure 3. A fitting curve corresponding to crosswind is shown in Figure 3. Slopes are different between two adjustments from up to crosswind and from down to crosswind direction. Figure 4 depicts $S36$s before and after the anisotropic correction. In almost range of SeaWinds wind speed, $S36$ becomes flat to RWD. But, at larger wind speed such as 19m/s, there remain small differences among RWDs with an order of 1K.

![Figure 3 - Method of correcting the anisotropic feature of S36. S36 (horizontal axis) and $T_{6H\ast}$ (vertical axis) are shown for ten cases of the SeaWinds wind speeds and for three cases of RWDs. S36 under up and down wind directions are adjusted to the one under crosswind direction (fitting curve), using slopes depicted by solid lines in both sides.](image-url)
Finally, S36 is converted to wind speed, using a curve shown in Figure 5, obtained by comparing S36 with the SeaWinds wind speed, in which the number of collocated data is about $3 \times 10^8$ during seven months. Conversion of negative S36 values is prepared, since S36 sometimes becomes negative. Reasons of S36 becoming negative are (a) Tb temperature noise (fluctuation) of AMSR, (b) incorrect SST derived from the weekly SST. The remained error of corrected S36 (Fig. 4) will make a wind speed error. From the conversion curve, 1K error of S36 is estimated as 1m/s error of wind speed in the 15-20m/s range.
Retrieval accuracy
To examine the algorithm developed in the previous section, the AMSR wind speed was compared with ocean buoy’s ones. Ocean buoys data were collected from moored buoys of the National Data Buoy Center (NDBC), Tropical Atmosphere Ocean (TAO) Project, and Prediction and Research Moored Array in the Atlantic (PIRATA) in open ocean off 100Km from shorelines. Heights of measured wind speed are different among buoys, which were adjusted to 10m by assuming a neutral atmospheric condition. In combing the AMSR and buoy data, a time difference between the AMSR and buoy measurements was limited within one hour. Nine pixels data of the AMSR were averaged around buoy location. The bias of AMSR minus buoy wind speed is –0.008m/s, and RMS of differences is 0.954m/s for entire data during seven months in 2003. The number of collocated AMSR and buoy data is about 3200 during its period.

Summary
The algorithm of retrieving wind speed for AMSR was developed by combining the AMSR and SeaWinds data. The developed algorithm was applied to wind speed comparison with buoys, and results similar to the SeaWinds were obtained. The current combination of AMSR and SeaWinds in ocean regions may be one of good examples of combining passive and active microwave sensors. The developed algorithm can also be applied to the AMSR-E, which was almost similar to AMSR. The AMSR-E was aboard the NASA Aqua satellite launched in May 2002, and the AMSR-E stopped in October 2011. The algorithm will be also applied to AMSR2 aboard the Global Change Observation Mission – Water (GCOM-W) in plan to be launched in middle 2012 by JAXA.

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