Sea surface temperature observation through clouds by the Advanced Microwave Scanning Radiometer – 2

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ABSTRACT: Sea surface temperature (SST) is an important parameter used in many applications, such as fisheries, weather forecasting as boundary condition, and monitoring of climate changes. In these applications, SST is necessary under both fine and cloudy conditions, which can be made by passive microwave radiometers in particular under cloudy condition. To measure SST by microwave radiometers, frequencies below 10GHz are necessary, but measuring SST colder below around 10C becomes difficult using 10GHz. The frequency 6GHz is necessary for measuring SST in global oceans. The Advanced Microwave Scanning Radiometer -2 (AMSR2) aboard the Global Change Observation Mission – W (GCOM-W) of the Japan Aerospace Exploration Agency is one of such sensors, and began SST observation since July 2012. AMSR-2 is a successor sensor of AMSR-E aboard the NASA AQUA satellite, whose SST observation was made from July 2002 to October 2011. Algorithms retrieving SST from AMSRs should be developed by keeping minds of several points: (1) wind effect corrections on brightness temperature for both wind speed and direction, (2) removal of radio frequency interference from several sources, (3) accurate calibration of brightness temperature of AMSRs, (4) removal of sea ice area, and (5) removal of land contamination. In this paper, those techniques developed for AMSR SST retrieval will be presented.

1. Introduction

There are two sensors to observe sea surface temperature (SST) from space borne satellites; one is an infrared sensor, and the other is a microwave sensor. Features of the former sensor are a capability to observe a target (e.g. ocean eddies) with a fine scale such as 1Km, a light weight as space sensor. But, infrared sensor can’t observe SST through clouds. Feature of the microwave sensor is a capability to observe SST through clouds. But, spatial resolution of the microwave SST is generally low such as 40-60Km, and a weight of the microwave sensor is heavy.

Operational observations of infrared SST by the Advanced Very High Resolution Radiometer (AVHRR) started in 1981, and have become one of standard methods to observe SST up to the present. A reliable microwave SST observation was firstly made in 1997 by the TRMM Microwave Imager (TMI) aboard the Tropical Rainfall Measuring Mission (TRMM) of U.S. - Japan joint project. Though the TMI SST observation is limited in a SST range higher than 10C, it continued to 2014. Next microwave SST observation was started in 2002 by the Advanced Microwave Scanning Radiometer –E (AMSR-E) aboard the NASA AQUA satellite, which made global SST observation even below 10C. In late 2002, more two microwave SST sensors were launched; one is the AMSR aboard the Advanced Earth Observing Satellite – II (ADEOS-II) of the Japan Aerospace Exploration Agency (JAXA), and the other is the Windsat of the U.S. Navy. Unfortunately, the ADEOS-II stopped its operation in 2003 due to a failure of power cable from solar panel to satellite bath, but the Windsat is continuing its operation up to the present. Also, the AMSR-E stopped its operation in 2011 due to a failure of driving motor for a main reflector. Recently, a successor sensor of AMSR-E, i.e., AMSR-2, started SST observation in 2012, which is aboard the Global Change Observation Mission – W (GCOM-W) of JAXA. Three AMSRs (AMSR-E, AMSR, and AMSR-2) were manufactured by the JAXA.

To retrieve SST from the brightness temperature (Tb) of microwave radiometers, frequencies below 10GHz are necessary (Shibata, 2004, or as Fig.1 in this paper). In developing algorithms to retrieve SST from the microwave Tb, most difficult problem may be a removal of wind effect on the Tb. To remove the wind effect, two polarizations of the vertical (V) and horizontal (H) ones are necessary, since the H polarization is more sensitive to ocean wind than the V polarization. On the other hand, the V polarization at 6-10GHz is more sensitive to SST than the H-polarization. Combing the two polarization Tbs, a removal of the wind effect could be possible.

Second difficult problem in retrieving the microwave SST may be a removal of the Radio Frequency Interference (RFI) affecting Tbs. There are many sources of RFI at frequencies of 6-10GHz; ground based radar transmitted to another ground based receiver, ground based radar transmitted to space for geostationary satellites or non-geostationary satellites, and satellite borne transmitter to ground receiver. Their operations of radars are varying in time and space. Sometimes new radars suddenly appear and affect the Tb, or they disappear. Several techniques
combing the Tbs at several frequencies are necessary to remove the RFIs.

As another points to mention in retrieving SST, calibration of Tbs, removal of sea ice area, removal of land contamination, and incidence angle correction can be listed. In this paper, those corrections will be described, and finally SST accuracy retrieved from AMSR2 will be reported as validations.

2. AMSR sensor

The frequencies of AMSRs are 6, 10, 18, 23, 36, and 89GHz, where both V and H polarizations are available in all frequencies. The ADEOS-II AMSR additionally had two frequencies (50 and 52 GHz) of V-polarization, and the GCOM-W AMSR2 additionally has 7GHz of both polarizations, which can be used to remove RFIs. Spatial resolutions of the lowest frequency 6GHz are from 35 × 65 Km (AMSR2) to 43×75Km (AMSR-E), depending on each satellite height and each main reflector’s diameter. Spatial resolutions of 89GHz are from 3 × 5 Km to 4×5Km. The main reflector of each AMSR rotates at 40 rpm, which enables 10Km spatial sampling on the Earth surface in two directions; one is along a rotating direction, and the other is along a satellite moving direction. This is valid for all frequencies except for 89GHz. The spatial sampling of 89GHz is 5Km, because the frequency 89GHz has two horns (A and B), and each horn sees the Earth simultaneously at a different incidence angle. An incidence angle on the Earth surface is all 55degree except for 89GHz B, of which incidence angle is 54.5. A temperature resolution of 6GHz is 0.3K, and the one of 89GHz is 1.2K. More detailed descriptions of the AMSR sensor are found in the paper (Kawanishi, et al., 2003).

3. SST retrieval algorithm

In AMSR SST retrieval algorithm, all frequencies except for 89GHz are used. Main frequency to retrieve SST is 6GHz, and sub one is 10GHz. Fig.1 shows a relation between SST and Tbs at 6 and 10GHz V polarization (6V and 10V), in which the horizontal axis is SST, and the vertical axis is Tb at two frequencies. In calculations to derive the Fig. 1, the Fresnel equation is used, and the complex dielectric constant of sea water is adopted from the paper (Klein and Swift, 1977). The incidence angle is 55 degree. In this figure, small adjustments are made on the theoretical Tb, matching with AMSR 6 and 10GHz Tbs.

From this figure, following points are noticed: (1) a response of 6V to SST is 0.5K/C for SST higher than 10C, and its response becomes smaller as 0.3K/C around SST 0C, (2) the one of 10V shows a similar value for SST higher above 20C, but it becomes 0.3K/C around SST 10C, and almost zero around SST 0C. From these relations, an appropriate frequency to retrieve global SST is 6GHz rather than 10GHz. The TMI aboard the TRMM had only frequency 10 GHz. The response of the horizontal polarization is about half of the vertical polarization.

3.1 Atmospheric corrections

Two Tbs of 23V and 36V are used to remove an atmospheric effect on 6 or 10GHz. To do this, a microwave model transferring in the atmosphere and reflecting on the ocean surface was made (Shibata, 2004). Using this model, an atmospheric effect, Atmos_effect, is derived as eq.(1),

\[
\text{Atmos}_{\text{effect}} = \text{Tb}_{\text{space}} - \text{Tb}_{\text{ocean}}, \quad (1)
\]

where Tb_space is a model derived Tb as observing the Earth at a satellite height, calculated for 6 and 10GHz at two polarizations. Tb_ocean is the Tb shown as the vertical axis of Fig.1 in the case of the vertical polarization. Atmos_effect means a contribution of emissions from molecules of oxygen and water vapor, and from liquid water in the atmosphere. Corresponding to Atmos_effect at 6 and 10GHz, Tbs of 23V and 36V are calculated at the satellite height. The vertical polarization is used, since it is less sensitive to ocean wind than the horizontal one as explained earlier. Then, a table of reading Atmos_effect is made using two values of 23V and 36V, which is shown as Fig.2 in the paper (Shibata, 2004).
Values of Amos_effect at 6V change from 5K to 8K. A minimum value of 5K corresponds to the atmosphere with only oxygen without both water vapor and liquid water. An increasing value up to 3K from this 5K corresponds to contributions from water vapor and liquid water. In precipitating clouds, the microwave is scattered by raindrops. In this case, the current microwave transferring model can’t be used, because the current model doesn’t include scattering processes by raindrops. To exclude precipitating cases, an upper limit of 6.6K for Atmos_effect is set, which is determined by comparing with AMSR’s Tbs.

3.2 Wind effect corrections

Wind effects on the Tbs can be estimated by examining following parameter, Tb_wind, as defined in eq.(2),

\[ \text{Tb}_{\text{wind}} = \text{AMSR}_\text{Tb} - \text{Atmos}_\text{effect} - \text{Tb}_\text{ocean}, \]

(2)

where AMSR_Tb is the Tb observed by the AMSR at 6 and 10GHz at two polarizations, and Atmos_effect and Tb_ocean are the same in eq.(1). Fig.2 shows these Tb_wind of 6GHz at two polarizations, where the horizontal axis is the H-polarization, and the vertical one is the V-polarization (Shibata, 2006). This figure is obtained by using all data of ADEOS-II AMSR in global ocean during 7 months between April and October 2003. In this figure, three relative wind directions (upwind, crosswind, and downwind) are shown, which are defined as an angle made by two angles; the AMSR viewing angle and wind direction retrieved from the SeaWinds. The SeaWinds was a scatterometer, an active microwave sensor operating at 13GHz to measure the ocean wind speed and direction. The SeaWinds was made by the NASA, and also loaded on the ADEOS-II.

From Fig.2, the wind effect on 6V, i.e. d6V, can be estimated by using Tb_wind of 6H, as expressed in eq.(3),

\[ d6V = \begin{cases} 0 & \text{for } \text{Tb}_{\text{wind}} \text{ of } 6H \leq z, \\ (\text{Tb}_{\text{wind}} \text{ of } 6H - z) \times s & \text{for } \text{Tb}_{\text{wind}} \text{ of } 6H > z, \end{cases} \]

(3)

where z is a constant (=3.4K from AMSR data), and s is a slope depending on relative wind directions; s is roughly 0.67 for upwind, and 0.47 for both cross and downwind directions. To know the relative wind direction, additional parameter, S36, is necessary. S36 is derived from 36V and 36H, and a detailed method of getting the relative direction is described in the paper (Shibata, 2012). Furthermore, d6V changes also with a difference of air temperature and SST (i.e. it depends on the atmospheric stability), and a detailed description of features is found in the paper (Shibata, 2007).

3.3 Removal of RFIs

Here, two examples of RFI observed by AMSR2 will be shown, in which two combinations (6V and 10V, and 6H and 7H) are used to remove RFI. In another cases of RFI, techniques are slightly different among cases depending on each RFI. Fig.3 shows the RFI of 6V around the Ascension Island in the southern Atlantic Ocean, where ground radar transmits the microwave to geostationary satellite. Though these RFIs are observed several times in a year, their strengths are very strong as 30-40K as shown in Fig.3. In natural status of ocean surface, 6V and 10V are correlated with a line of slope 1.1as shown in Fig.3. The RFI of the Ascension Island affects 6V as negative values.
Second example is shown in Fig.4, where Tbs of 6H and 7H are displayed. The Tbs in Fig.4 are original values as observed by the AMSR2. In natural status of ocean surface, 6H and 7H are correlated with a line of slope 1 with a small positive offset for 7H. In this RFI, 6H increases by a few Kelvin. This RFI may be caused by transmitters aboard non-geostationary satellites, where the microwave is transmitted to the Earth and then reflected on ocean surface.

As shown in Figs. 3 and 4, it is difficult to divide natural signals and RFIs in weak RFI status. To make a severe judgment for RFI, many natural ocean signals would be judged as RFI and lost in SST retrieval, which may be an unacceptable case in SST algorithm developments.

3.4 Calibration of Tbs

As shown in Fig.1, the ratio of the microwave Tb to SST is from 0.5 to 0.3 K/C at 6V. To achieve a SST accuracy of 0.1C, the Tb of 6V should be calibrated with an order of 0.05K. For sensors operating in space, this value might be severe for achievement, in particular for the AMSR-type sensor, where a hotload used for a calibration at around 300K is put on an outside of the sensor. At the present, the AMSR 6V Tb is calibrated with SSTs measured by ocean buoys.

3.5 Removal of sea ice areas

As shown in Fig.1, the 6V emissivity of ocean surface is 0.57 at SST around 0C. On the other hand, the emissivity of sea ice is near 1.0. So, the microwave emission of sea ice affects the ocean 6V Tb, if sea ice exists within a pixel of AMSR footprint (40-60Km). Even existing in a neighborhood of the pixel, the ocean 6V Tb is still affected, because the sea ice emission comes in through a side-lobe of AMSR antenna. Furthermore, the microwave features of sea ice are changeable with its type or condition. So, in SST retrieval algorithm, all frequencies except for 89GHz are used to find a sea ice. The 89GHz Tbs are not used in the current algorithm, since they are seriously affected sometimes by weather conditions.

3.6 Removal of land contaminations

Similar to sea ice, a land emission affects the ocean 6V Tb. The emissivity of lands is also near 1.0. Comparing with sea ice, land locations are fixed. So, exact values of land contaminations can be evaluated by using an antenna pattern of AMSRs, where the emission of lands entering through a side-lobe of antenna can be calculated with an order of 0.1K or less.

3.7 Incidence angle correction

The incidence angle of each pixel changes with satellite’s attitude and satellite’s position. In AMSR case, the incidence angle takes a value of 55.0 ±0.1. To retrieve an accurate SST, the incidence angle correction should be made. Eq.(4) shows a correction, dT, due to an incidence angle variation in AMSR case,

\[ dT = a \times (\text{Angle} - 55.0), \quad (4) \]

where a is a correction coefficient, and Angle is an incidence angle of each pixel. The correction coefficient depends on frequency and polarization. As low frequency of 6 and 10GHz, the coefficient depends also on SST. On the other hand, at high frequencies above 18GHz, the coefficient depends on the atmospheric opaque. In this case, the atmospheric opaque is approximately expressed linearly by the Tb itself, as shown in eq.(5),

\[ a = a_0 - b \times (\text{Tb} - c), \quad (5) \]

where a0, b, and c are constants depending on frequency and polarization, and Tb is the brightness temperature itself. Constants, a0 and c, represent a status of most transparent atmosphere, and the constant, b, represents a level of the atmospheric opaque.

4. Validations

Accuracies of the microwave SST retrieved from AMSR2 were evaluated by using ocean buoy. Only drifting and moored ocean buoys were used. Data of buoys sometimes include errors. This happens in a case that a bit error occurs in data. Or, errors could happen in a beginning of buoy operations, where buoys might be put on a deck of ship, not in ocean. In an ending of buoy operations, errors also could happen, where a SST sensor of buoys might be degraded. Before comparing with AMSR2 and buoy SSTs, those errors of buoys were excluded.
Table 1 shows a summary of AMSR2 SST accuracy. Unit of RMSE and bias is degree, and a number of collocated data is listed in the bottom. Day means data observed in daytime, and night means nighttime. A period of collocated data is between July 2012 and March 2015. The accuracy of both AMSR-E and AMSR is similar to AMSR2 (Shibata, 2004).

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Table 1 AMSR2 SST accuracy

5. Conclusions

About 18 years has passed since the microwave SST observation started. During this period, two major sensors played important roles (AMSR-E and AMSR2). The SST accuracies of three AMSRs are almost the same, in which the AMSR2 accuracy is listed in Table 1. These SST accuracies might be enough for utilization in many applications in ocean. In fact, the Japan Meteorological Agency (JMA) has used the AMSR-E and AMSR2 SST since 2004 in their SST analysis. The JMA use this SST analysis as a boundary condition of ocean surface for a numerical weather forecasting. The Japan Fisheries Information Service Center (JAFIC) has also used the AMSR-E and AMSR2 SST in the JAFIC’s analysis of fisheries condition. It is now clear that the microwave SST retrieved from AMSRs is accurate as required from operational users, and it is desirable that AMSR2-followings would continue as operational sensors in future.

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References