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A BASIC STUDY ON A NEW SATELLITE ALGORITHM FOR SNOW BY CONSIDERING THE EFFECTS OF SNOW GRAIN SIZE

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SYNOPSIS

In this paper, a new algorithm for snow depth and snow particle grain size is developed based on a microwave radiative transfer theory, and validated by using the in situ snow depth data at 65 ground-based stations in the northern hemisphere and the Advanced Microwave Scanning Radiometer

for the Earth Observation System (AMSR-E) on Aqua launched by NASA in 2002. In the case of snow depths of less than 40cm, there was good agreement between the observed and estimated values. However, for the snow depths of more than 40cm, it is argued that a lower frequency should be used in an algorithm.

INTRODUCTION

Various climate conditions can be found over the global and depend on the variation of water cycle over the land, in the atmosphere and the ocean. Various land surface conditions are formed by vegetation and snow. Moreover, spatial and temporal heterogeneity over the land is more remarkable than for example on the ocean. Therefore it is difficult to grasp the hydrological variation over land quantitatively. On the other hand, if we can establish an earth scale observation system to observe hydrological variations, then we can predict fluctuations of long-term global and short-term water-resources.

Snow affects the hydrological conditions of the land surface due to its high reflectivity and its effect on the heat balance. Therefore, snow affects greatly the climate variation on a global scale. In order to grasp snow conditions quantitatively, it is necessary that the observation instrument be arranged uniformly over land. However, it is from the viewpoint of the observation scale. Hence, the application of satellite remote sensing for snow observations was developed by improving the microwave observation technique using multi-frequency channels. In addition, development of all-weather snow observation methods which utilizes a microwave radiative instrument has been the focus of much research.

This paper devises a satellite algorithm, which automatically estimates the snow particle grain size, the snow depth, and the snow water equivalent quantity and the snow density based on the microwave radiative transfer basis theory. Finally, we evaluate the validity of the algorithm by marking a comparison between estimated snow depth and observed snow depth.

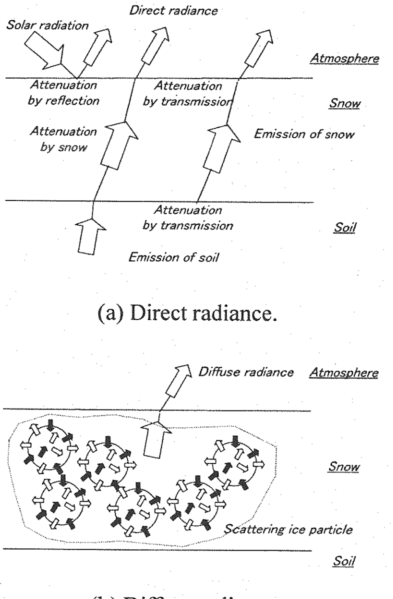
DERIVATION OF THE SNOW QUANTITY CALCULATION ALGORITHM

In this section, we describe the method for calculating the snow depth and the selection of a microwave radiative transfer model and the structure of an algorithm.

Method for Snow Depth Calculation and the Selection of a Microwave Radiative Transfer Model

Many methods have been developed for calculating snow depth. Koike and Suhama(1993) (1) applied a microwave radiative transfer model by England (1975) (2) to snow. They proposed a microwave radiative transfer model from snow layers shown in Fig.1. England's model (1975) is a model based on the theory that radiation from a scattering medium consists of two components: the direct radiation and the diffuse radiation. In addition, this scattering medium is a medium of homogeneous thickness of average (D) including spherical scatterers of average number (N) on a half-infinite medium. In this an algorithm, the scattering medium is assumed to be snow layers which consist of uniformly spherical ice particles. On the other hand, the half-infinite medium was assumed to be soil. Moreover, the direct ratio brightness can be calculated by solving the following two equations: One equation is the ratio of brightness balance equation at the two boundaries atmosphere/snow and snow/soil. The other one is the radiative balance equation within snow layer.

This model calculates the diffuse ratio brightness using the radiative transfer equations where by extinction was produced in the transfer process within the snow layers of the scattered emissions of an ice particle. Both the extinction and the emission scatter were calculated by means of the Rayleigh model approximation. The scattered component of both the direct and diffuse emissions by the Rayleigh's scattering phase function is expressed. Moreover, the diffuse emissions were calculated by integrating this phase function across all azimuths.



(a) Direct radiance.

(b) Diffuse radiance.

Fig.1 Microwave radiative transfer model for snow.

We calculated both the direct brightness temperature by and the diffuse brightness temperature using the Rayleigh - Jeans model approximation. On the other hand, Koike *et al.*(1999) (3) assumed snow particle grain size and the snow density in England's model (2). Snow depth and snow temperature were shifted at the same time. Concurrently, snow depth and snow temperature were shifted and brightness temperature from snow layers corresponding to two frequencies was calculated. A table for changing snow depth and snow temperature into brightness temperature was constructed corresponding to the two frequencies based on the result of this calculation. Moreover, a table was created for transforming the two frequencies into snow depth and snow temperature by completely complementing the brightness temperature of this table. Furthermore, the snow quantity calculation algorithm was developed which was used to calculate snow depth and temperature from the brightness temperature corresponding to two frequencies. However, the application of this algorithm is limited to dry snow because it uses the property of scattering extinction and scattering emission which changes significantly with different frequencies. Hence, the input values for snow temperature and soil temperature must be equated in this algorithm.

In this research, the first step taken was to apply the snow quantity calculation algorithm used by Koike *et al.*(1999) (3), and then we constructed a table for transforming the two frequencies into snow depth and temperature. The snow density was assumed to be 0.3 g/cm^3 and the snow particle grain size to be 0.7 mm. The snow depth changed between 1cm to 200cm in steps of 1cm and the snow temperature changed between 243K to 273K in steps of 1K. These values were input to England's model. The results are calculated brightness temperatures for two frequencies (19GHz and 37GHz). These findings are shown in Fig.2.

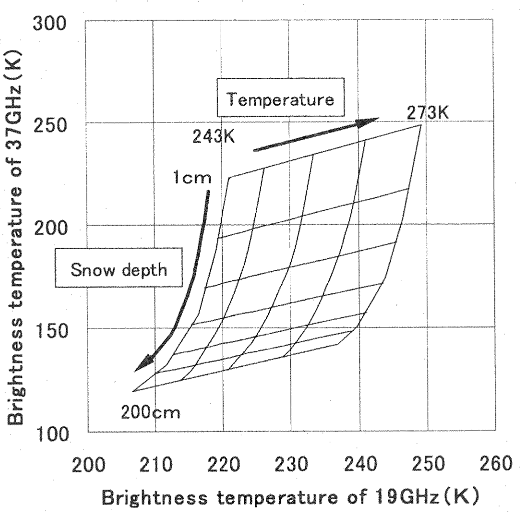


Fig.2 The relationship between the calculated brightness temperatures (19GHz, 37GHz) and the snow depth and temperature.

Subsequently, we verified the position relationship between satellite brightness temperatures and a transformation table. At this point, AMSR-E satellite brightness temperature data of the northern hemisphere for 65 sites from October 2002 to March 2003 was used. I was found that the high brightness temperature did not enter the transformation table. An example of this is shown in Fig.3. It became unnecessary to use temperatures exceeding 273K because snow melts above this temperature. Therefore, we considered taking the following countermeasures: 1) The condition was found where soil-exceeding 273K is covered with snow. 2) The temperature component was changed to the soil temperature from the snow temperature.

However, England's model was not able to reproduce these same conditions. The reason for this is that snow and soil temperature should be equal in this model. Consequently, it is difficult to apply this model in this case.

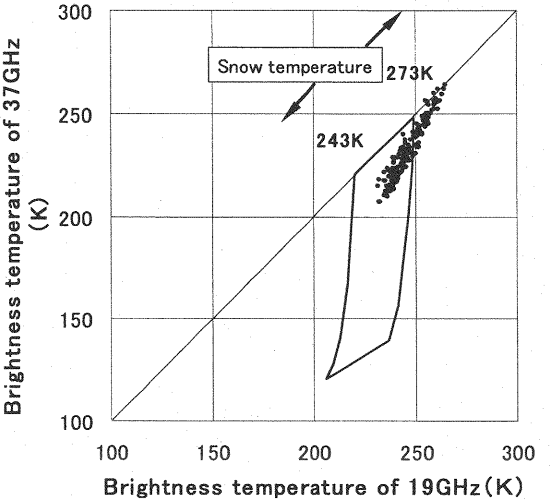


Fig.3 An example of the position relationship between the satellite brightness temperatures and the transformation table based on England's model.

Hence, we applied to the 4-stream fast radiative transfer model developed by Liu (1998) (4). Originally, the 4-stream fast model was developed for application to the atmospheric layers between the ground and the satellite microwave radiometer. In this model, we reproduced the condition where a snow layer exists between the ground and the satellite microwave radiometer and applied the Greenstein scattering phase function for its scattering phase function. In addition, England's model differ greatly in that the snow and soil temperature can be set at different temperatures. Hence, this model can reproduce the right conditions where soil temperatures exceeding 273K can exist under snow. On the basis of this characteristic, snow depth varies between 1cm to 200cm and the soil temperature is limited in this model to every 1K from 243K to 303K. When the soil temperature was in the range from 243K to 273K, we made snow and soil temperature the same. When soil temperature exceeded 273K, we set snow temperature to 273K. By using this setting, a table for transforming snow depth and soil temperature into a brightness temperature of two frequencies (19GHz, 37GHz) was constructed and then interpolated to transform brightness temperature of two frequencies into snow depth and soil temperature. The results of experiment are shown in Fig.4 where it may be seen that the satellite brightness temperatures of almost all of the sites were distributed within this transformation table.

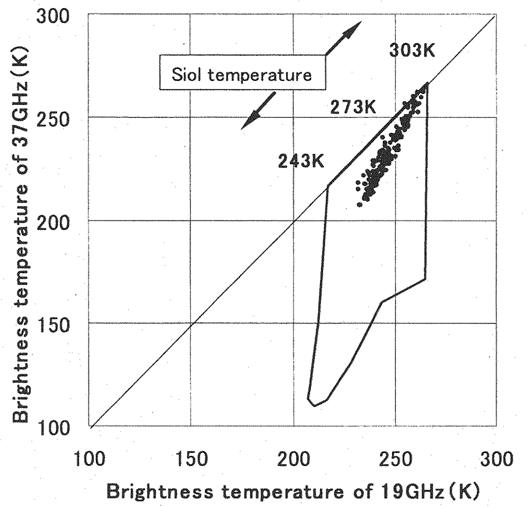


Fig.4 Position relationship between the satellite brightness temperatures and the transformation table based on the 4 - stream fast model.

The Structure of Algorithm

Finding showed that it is possible to calculate snow depth and temperature (soil and snow) from the satellite data of only two frequencies using the aforementioned transformation table. However, this calculation relies on the assumption of snow particle grain size. Hence, when it is assumed that the snow particle grain size is greatly different from the actual size, it is possible that a considerable discrepancy will arise when the snow depth is large. On this basis, we devised a snow quantity calculation algorithm which can be used to calculate snow depth and temperatures (soil and snow) after detecting snow particle grain size automatically only from the satellite data. The flow of an algorithm is as follows and is shown in Fig.5.

1) This algorithm assumes snow particle grain sizes of 0.3mm, 0.4mm, 0.5mm, 0.6mm, 0.7mm and 0.8mm using the two frequencies 19GHz and 37GHz. On this basis, it calculates the transformation table (snow depth transformation table) that transforms the brightness temperature of two frequencies into snow depth and soil temperature for every particle grain size. At the same time, this algorithm calculates the transformation table (brightness temperature transformation table) that transforms snow depth and soil temperature into brightness temperature for two frequencies for every corresponding particle grain size. The corresponding particle grain size is a particle grain size corresponding to 10GHz, which corresponding to six particle grain size types used when the snow depth transformation table was calculated.

2) The algorithm can calculates snow depth and soil temperature by inputting the satellite brightness

temperature of 19GHz and 37GHz into each snow depth transformation table. 10GHz brightness temperature is calculated by inputting this calculated value into each brightness temperature transformation table.

3) It can also calculate the modulus of difference in the calculated brightness temperature and the satellite brightness temperature (brightness temperature difference).

4) Lastly, it compares the brightness temperature difference corresponding to each grain size, and selects the minimum brightness temperature difference. It then decides on the snow particle grain size, snow depth and temperature corresponding to the selected value. This results in quantification of snow. The above process describes snow quantity calculation algorithm in this paper.

Moreover, it became possible to calculate the snow quantity of snow using this algorithm shown below:

1) The snow depth was calculated using the brightness temperature for two frequencies (19GHz, 37GHz).
2) The snow temperature was then found using the relationship between snow temperature and soil temperature on the initial conditions.
3) The snow particle grain size was detected using the satellite brightness temperature of 10GHz.
4) The snow water equivalent was then calculated using the assumptions for snow density, snow depth and snow cover area.

In the next section, we will explain the corresponding particle grain size used when calculating 10GHz brightness temperature transformation table. Snow particle grain size should essentially be a geometric value, and should serve as a fixed value, unrelated to the difference in frequencies. However, in the present the 4-stream fast model, we found that the calculated value of brightness temperature differed greatly when the snow particle grain size corresponding to a high frequency was used for a low frequency. We calculated the particle grain size corresponding to brightness temperature (19GHz and 37GHz) as realistic snow particle grain sizes, and we found the relative relationship of the particle grain size corresponding to 10GHz and the particle grain size corresponding the 19GHz and 37GHz brightness temperature. That relative relationship is shown in Fig.6.

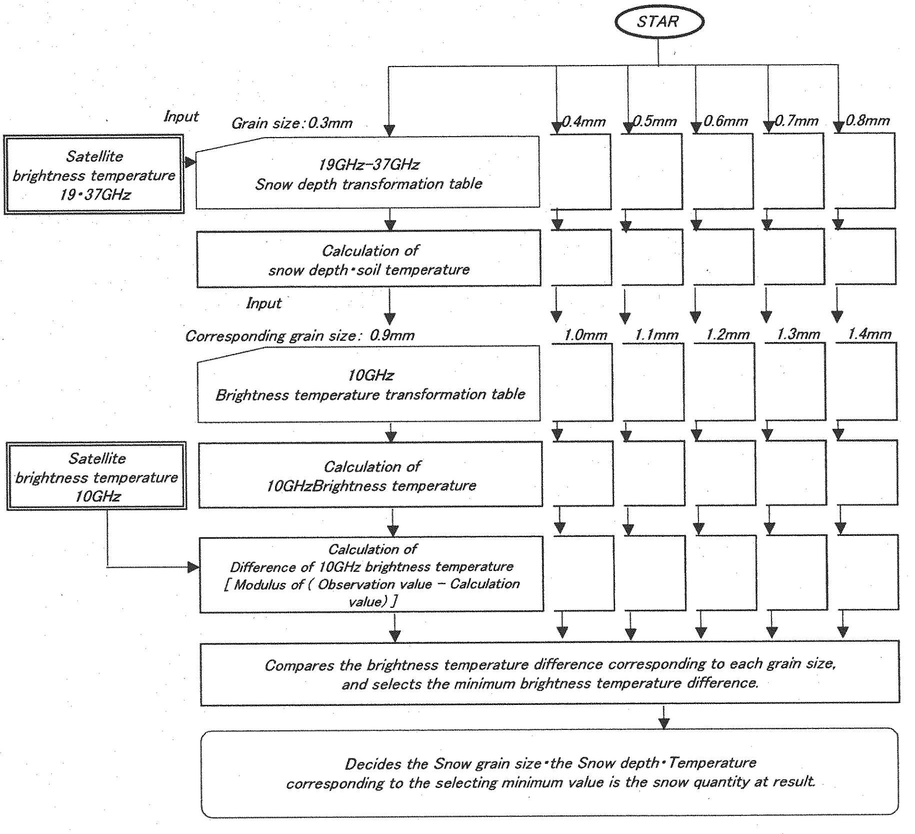


Fig.5 Flow chart of the snow quantity calculation algorithm.

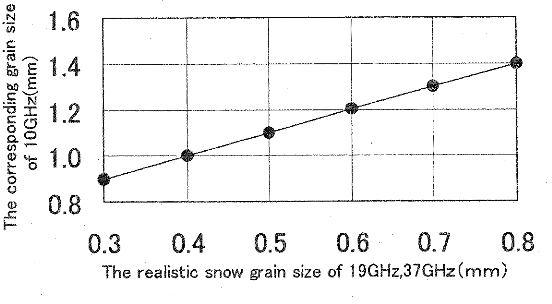


Fig.6 Relative relationship of the realistic grain size and the imaginary corresponding particle grain size.

We were not able to find an optimum snow particle grain size by mean of the discrepancy in relationship of realistic particle grain size and corresponding particle grain size. However, these relative relationships solved this problem. Hence, this adjustment is the key to the results of calculations using this algorithm.

THE ESTIMATION OF THE DEVISED SNOW QUANTITY CALCULATION SATELLTE ALGORITHM

In this paper, we estimated the validity of our algorithm by comparing the calculated snow depth based on our algorithm and the GTS snow depth data. The findings below were made by determining the average of modulus of difference between the observed value and the calculated value as the estimation index. 1) When this value is 20cm or less, this compatibility is good. 2) When this value exceeds 20cm, the compatibility is poor. The results are as follows; Good compatibility: 37 sites among 65 sites. Poor compatibility: 28 sites among 65 sites. Moreover, we found that the compatibility conditions of 40cm or more differed from the compatibility conditions of less than 40cm significantly. In view of this state of this condition, we checked the compatibility of 41 sites whose observed snow depth is 40cm or less within a specified period. Consequently, the following relatively useful findings were obtained: Good compatibility: 33 sites among 41 sites. Poor compatibility: 8 sites among 41 sites. A scattering diagram between the calculated values and the observed values is shown in Fig.7. One example of the relationship between calculated values and observed values is shown in Fig.8. This figure shows the increase inclination of snow particle grain size accompanying snowy aging is estimated by using an algorithm.

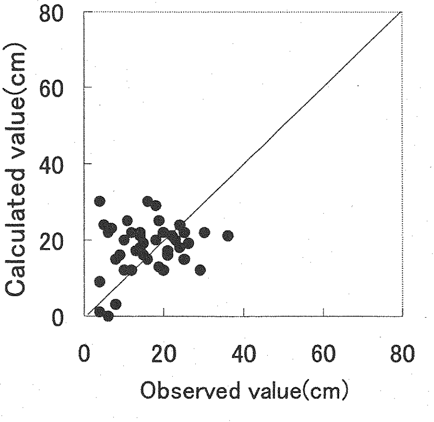


Fig.7 Scattering diagram of calculated values and observed values.
Observed snow depth: 40cm or less.

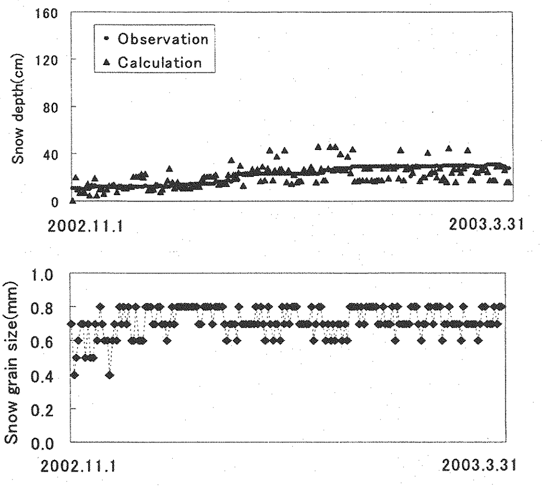


Fig.8 An example of the relationship between calculated value and the observed value.

Observed snow depth: 40 cm or less.

On the other hand, during the specified period, the following conclusions were made for the 25 sites where the snow depth exceeded 40cm; Good compatibility: 4 sites among 25 sites. Poor compatibility: 20 sites among 25 sites. As shown in Fig.9 (Scattering diagram of calculated and observed values), the calculated values are very much smaller that observed values. One example of the relationship between calculated values and observed values is shown in Fig.10.

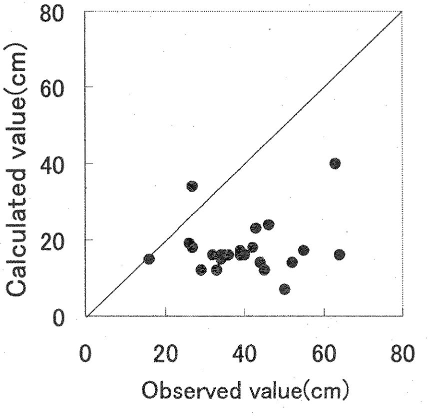


Fig.9 Scattering diagram of calculated versus observed values.

Observed snow depth: exceeds 40cm.

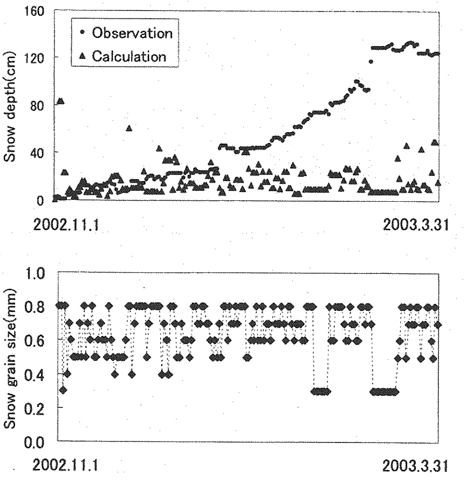


Fig.10 Example of the relationship between the calculated and observed values.
Observed snow depth: exceeds 40cm.

Hereupon, we examined the lack of the compatibility at the sites exceeding 40cm. Compatibility for snow depth of 40cm or less was found to be good for these sites. However, a calculated value cannot rise beyond a certain constant value when an observed value exceeds 40cm. This situation results in a poor compatibility and shown in Fig.10. Moreover, this situation means this algorithm cannot estimate for high snow depths exceeding 40cm by this algorithm. The application of the 4-stream fast model allowed us to apply multiple frequencies, and the selection of an optimum snow particle grain size. However, this model as well as the existential model over-estimates attenuation with scattering by snow particle while the attenuation by scattering at high frequencies is more remarkable than low frequencies. Hence, the snow depth transformation table based on the brightness temperature difference between 18GHz and 36GHz becomes long in the snow depth direction. In other words the interval of snow depth direction becomes large. Consequently a long snow depth transformation table cannot estimate deep snow.

As a consequence, this model cannot estimate deep snow by excessive evaluation of attenuation with scattering. This causes a deficiency in the estimated accuracy of snow depth, which exceeds 40cm. Hence, as shown in Fig.11 (World distribution map of compatibility), in order to calculate exactly the snow depth for an area of poor compatibility (Russia federal northern part and North America eastern part), it is necessary to examine the following matters:

1) The addition of an algorithm condition using a high frequency (89GHz) that is sensitive to changes in the snow particle grain size.
2) The application of a microwave radiative transfer model which evaluates exactly attenuation by scattering.

3) The application of a low frequency that can detect the land surface condition under snow pack to the algorithm.

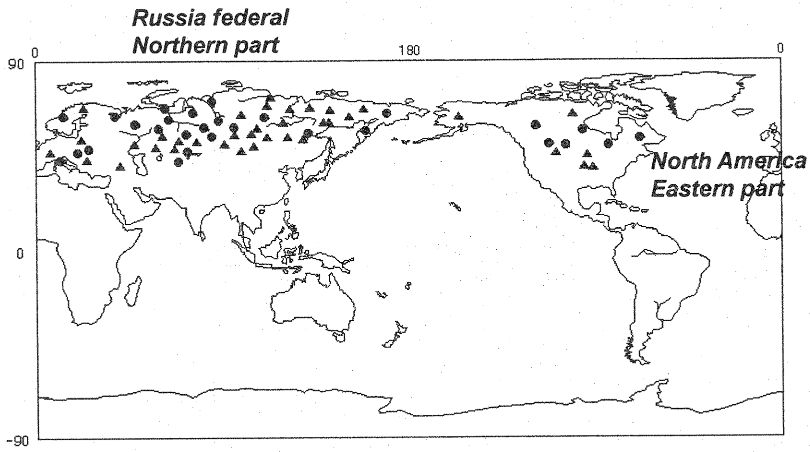


Fig.11 World distribution map of compatibility.

▲ : Good compatibility ● : Poor compatibility.

CONCLUSIONS

The following conclusions can be made from this research.

1) A satellite algorithm that calculates snow depth, temperature and snow particle grain size from the satellite microwave brightness temperature of three frequencies was suggested by the simulation using a microwave radiative transfer model in snow layers.

2) The results of the algorithm verification using observed snow depth from the northern hemisphere showed good results for more than half of the sites. At the same time, when observed snow depth was limited to 40cm or less, the results obtained were comparable for the whole of the site 80% or more of the time.

3) To further improve the calculation accuracy at sites where observed snow depth exceeds 40cm, three important topics are suggested as follows:

- Addition of an algorithm condition using a high frequency (89GHz).
- Application of microwave radiative transfer model which evaluates exactly attenuation by scattering.
- The application of a low frequency to the algorithm.

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