Calibration and Temperature Retrieval of Improved Ground-based Atmospheric Microwave Sounder

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Abstract — Calibration and retrieval are two important and critical techniques for ground-based atmospheric microwave sounder. Adopting proper calibration methods will ensure a high sounding resolution. The paper uses two calibrated methods like LN2 (22–31 GHz and 51–59 GHz) calibration and sky tipping (22–31 GHz) to realize periodic calibration and using noise injection and in-built blackbody to realize internal calibration. Assuming the atmospheric temperature profile is known to 2 K (state-of-the-art with present remote sensors) and instrument noise is 1–2 K brightness temperature (achievable with current technology). The paper extracts several clear-air datasets randomly in the available radiosonde datasets. It derives atmospheric absorption spectrum from MPM93 model, and simulates brightness temperature using radiative transfer equation. In order to estimate atmospheric temperature profiles from the radiometer data, the algorithm of back-propagation neural network has been used. The retrievals yield good results in the temperature profiles from the surface to nearly 400 hPa. So, the prototype of improved ground-based atmospheric microwave sounding meets the requirements and using proper algorithm the retrieval results can be used in many fields.

1. INTRODUCTION

Microwave radiometer is one of primary instruments for earth and ocean observation because of its ability of working on all-weather and all-day. Ground-based atmospheric microwave sounder has the advantages of higher resolution at the bottom of troposphere, lower maintenance cost, easy to match and operate and so on.

2. DESCRIPTION OF SOUNDING PRINCIPLE

The principle of atmospheric temperature and humidity sounding is to measure the atmospheric (oxygen and water vapor) molecular rotating absorbing spectrum and its wings; all of them are pressure broadened and therefore complete the retrieval of temperature and humidity profiles. Where, the oxygen molecular absorbing spectrum at about 50–60 GHz can be used for retrieving temperature profiles and water molecular absorbing spectrum at about 20–30 GHz for retrieving humidity profiles.

![Figure 1: Opacity of microwave transmission.](image1)

![Figure 2: External cold load attached to the radiometer box.](image2)
Figure 1 shows that the high opacity of atmosphere microwave transmission [1] (oxygen and water vapor). In the band of 0–200 GHz, there are two lines of oxygen (detecting atmospheric temperature profiles) and water vapor (detecting atmospheric humidity profiles), respectively. Among them, the energy spectrum enhances gradually as the frequency becomes higher and higher. The oxygen lines are at 50–60 GHz (usually measures space-borne vertical distribution of atmospheric oxygen) and 118 GHz. The water vapor lines are at 22.235 GHz and 183.31 GHz [2].

Having the same principle and referring to MP3000A [3], the ground-based atmospheric microwave radiometer operates at k-band (22–31 GHz) and V-band (51–59 GHz), and retrieves the atmospheric temperature profiles and humidity profiles and obtains parameters like liquid water vapor, flux and delay and so on.

3. Calibration

3.1. LN2 calibration

One of absolute calibration standards is the liquid nitrogen cooled target [4] that is attached externally to the radiometer box. This standard — together with the internal ambient load — is used for the absolute calibration procedure.

The boiling temperature of the liquid nitrogen and thus the physical temperature of the cold load depend on the barometric pressure $p$. The radiometer’s pressure sensor is read during absolute calibration to determine the corrected boiling temperature according to the equation:

$$T_c = T_0 - 0.00825 \times (1013.25 - p)$$  \hspace{1cm} (1)

where, $T_0 = 77.25$ K is the boiling temperature at 1013.25 hPa. The calibration error due to microwave reflections at the LN/air interface is automatically corrected by the calibration software (embedded PC). It is recommended to wrap a plastic foil around the load + radiometer (wind protection) during absolute calibration to avoid the formation of condensed water above the liquid surface (caused by wind etc.).

3.2. Sky Tipping Calibration

Sky tipping [5] (tip curve) is a calibration procedure suitable for those frequencies where the earth’s atmosphere opacity is low (i.e., high transparency) which means that the observed sky brightness temperature is influenced by the cosmic background radiation temperature of 2.7 K. High opacity channels like all temperature profiler channels > 53 GHz are saturated in the atmosphere and must be calibrated by other methods. Sky tipping assumes a homogeneous, stratified atmosphere without clouds or variations in the water vapor distribution. If these requirements are fulfilled, the following method is applicable: The radiometer scans the atmosphere from zenith to around 20° in elevation and records the corresponding detector readings for each frequency. The path length for a given elevation angle $\alpha$ is $1/\sin(\alpha)$ times the zenith path length (often referred to as “air mass”), thus the corresponding optical thickness should also be multiplied by this factor (if the atmosphere is stratified).

The optical thickness is related to the brightness temperature by the equation:

$$\tau(\infty) = -\ln\left(\frac{T_{mr} - T_i}{T_{mr} - T_{B0}}\right)\sec(\theta)$$  \hspace{1cm} (2)

$T_{mr}$ is a mean atmospheric temperature in the direction $\theta$, $T_{B0}$ is the 2.7 K background radiation temperature and $T_i$ is the brightness temperature of frequency channel $i$.

$$T_{mr} = \int_0^\infty T(z)e^{-\tau(z)\sigma_a}dz$$ \hspace{1cm} (3)

$T_{mr}$ is a function of frequency and is usually derived from radiosonde data. A sufficiently accurate method is to relate $T_{mr}$ with a quadratic equation of the surface temperature measured directly by the radiometer.

The sky tipping calibrates the system noise temperature and the gain factor for each frequency without using a liquid nitrogen cooled target. The disadvantage of this method is that the assumption of a stratified atmosphere is often questionable even under clear sky conditions due to invisible inhomogeneous water vapor distributions.

So, LN2 method is mainly be used in v-band operating at 51–59 GHz, and TIP is mainly used in k-band operating at 22–30 GHz.
3.3. Internal Calibration

External calibration is to realize validation and calibrating periodically (every one year or half). Internal calibration [6] is to realize quasi-real-time calibration, and calibrate gain and noise of receiver, and avoid the affects of noise fluctuations and noise drifts.

The internal calibration period depends on short-term stability and can be 10–20 minutes with temperature-controller in relative stable environment. Internal calibration unit consists of noise injection block and in-built calibration blackbody, and both provide stable reference. Noise injection block consists of noise source (noise diode) which provides noise to be calibrated, switch which turn on and off the noise signal and directional coupler which is used for noise injection. We can used microwave switch or supply power to turn on and off the noise signal. Directional coupler is used for feeding into noise signal which temperature is 100–200 K.

Internal calibration blackbody provides standard brightness temperature (∼ambient temperature). To ensure the stability, there are many pt-resistances to measure the temperature gradients. In order to reduce the gradient, it is optimal to use foam material which has performance of insulation as blackbody calibration layer and DC mini-fan to drive the airflow.

Internal calibration unit has another function. It can correct nonlinear error by Noise injection method. Although ideal radiometer receiver is a linear system, nonlinear error caused by nonlinearity of detector diode and it is not negligible and mostly reaches to 1 K order.

The nonlinearity of detector can be as follows:

\[ U = G P^\alpha \quad 0 < \alpha < 1 \] (4)

where, \( U \) is the detector voltage, \( G \) is the detect-coefficient, \( \alpha \) is a nonlinearity factor and \( P \) is the total noise power that is proportional to the radiometric brightness temperature \( T_r \) according to Planck radiation law. The relationship between them is:

\[ U_2 = G' (T_{REC} + T_{COLD} + T_A)^\alpha \] (5)

\( G' \) (system gain), \( \alpha \) (nonlinear factor) and \( T_{sys} \) (noise temperature of receiver) are three unknown quantities. To correct nonlinearity of system, we generate four temperature points by additional noise injection of temperature \( T_n \). So there four independent equations with four unknowns (\( G, \alpha, T_{sys} \) and \( T_n \)) and than fit the nonlinear curve showing in Figure 2.

By injecting known noise-temperature into receiver, we can calibrate multi-points through nonlinear response. In the design, by observing low temperature and ambient temperature blackbody, there’re two calibration points \( T_c \sim U_1 \) and \( T_h \sim U_2 \), and other two points \( T_c + T_n \sim U_3 \) and \( T_h + T_n \sim U_4 \) after injecting noise. Then 3 calibration parameters and noise injection and then decide the nonlinear factor \( \alpha \) can be derived.

Noise temperature and gain of receiver change when ambient temperature changes. Internal calibration is a method which calibrates noise temperature and gain of receiver periodically through two known reference targets, then obtaining a real-time calibration equation to measure the real-time target brightness temperature.

4. REREIEVAL PRINCIPLE

In recent years, artificial neural network (ANN) has been used widely [7]. The structure of ANN shows in Figure 3. The layers 1, 2, and 3 represent the input layer, the hidden layer, and the output layer, respectively. The neurons of the input layer are represented by vector \( X_i \) \((i = 1, 2, 3, \ldots, n)\), where \( n \) is the number of the input neurons).

For the \( i \)th node in the hidden layer, this can be expressed as

\[ Y_j = S \left( \sum_{i=1}^{L} w_{ij} x_i + b_j \right) \] (6)

where, \( S \) denotes the sigmoid function,

\[ S(\alpha) = \frac{1}{1 + \exp(-\alpha)} \] (7)

where, \( w_{ij} \) is the weighting of the connection between the \( j \)th input neuron and the \( i \)th hidden neuron. \( b_j \) denotes the bias between calculated and measured values. Between hidden layers and output layers it uses purelin function.
5. SIMULATION RESULTS

The paper uses 225 radiosonde data. Choose 20% randomly as train sets and choose 20% randomly as tests. The input has 10 elements include 7 brightness temperatures (7 channels in v-band), troposphere temperature, troposphere pressure, troposphere height. The output includes 20 temperature values in 20 values of pressure from 1000 mba to 300 mbar or height from 0 to 10 km [8].

6. CONCLUSIONS

According to the radiative transfer equation, we retrieve the temperature from advanced prototype of ground-based microwave sounder. The neural network technique can derive the temperature weighting function by train the radiosonde datasets, and using other radiosonde datasets to test the model. Different temperature profiles of different regions can easily be retrieved using this method; also it can be used for different microwave sounders of ground-based and satellite platforms.
REFERENCES