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Errors Analysis and Improvement on Measurement Method for Microwave/Millimeter-Wave Emissivity of Small Targets by Radiometer

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ABSTRACT When using traditional methods to measure the microwave/millimeter-wave emissivity of small targets, errors arise due to that the antenna's main lobe and side lobe cannot be completely covered by the target. To eliminate the errors exist in traditional measurement methods, this paper first analyzes the main sources of errors and gives the analytical expression of the errors. On this basis, an improved method named voltage method is proposed. To test the effectiveness of the improved method, the horizontal polarization emissivity and the vertical polarization emissivity of a metal plate coat with stealthy nano-materials were measured at different observation angles by voltage method and traditional method, respectively. A dick radiometer working in 35 GHz is used in the experiments. Simultaneously, the accurate emissivities of the target are obtained by standard arch method. The results show that the voltage method improves the measurement accuracy largely compared to the traditional method.

INDEX TERMS Microwave/millimeter-wave, emissivity measurement, radiometer, error correction.

I. INTRODUCTION

Passive microwave/millimeter-wave (PMW/PMMW) technology has been widely used in many applications since it can penetrate smoke, fog, clothing, and can work day and night [1]–[6]. Accurate measurement of surface emissivity is essential in diverse fields such as remote sensing, materials classification and noncontact measurement of temperature [7]–[10]. Compared to radar, the PMW technology that uses a radiometer to measure (surface) emissivity has shown its superiority in price and operability. Currently, the emissivity of the targets' surface is generally derived by measuring the brightness temperature (BT) and the physical temperature of the target. In addition, the BT emitted from the environmental background must be measured individually [11], [12].

With the application of PMW detection in terminal guidance and security inspection, more attention has been paid to the measurement of PMW emissivity of coated materials for military targets, skin, and clothes. Therefore, the emissivity measurement for small targets becomes significant. However, the traditional method cannot eliminate the errors brought by the antenna side beam, and the errors rate of this method become intolerable especially when the foot print of the main beam exceeds the target area.

This paper first analyzes sources of the errors in the traditional measurement method from a theoretical perspective. Then an improved method named the voltage method basing on the radiometer measurement is proposed to eliminate the errors brought by the traditional method. Finally, experiments are conducted to compare the voltage method with the traditional method using a 35GHz Dick radiometer.

II. THEORY

A blackbody is an idealized body that represents a prefect absorber and a perfect radiator [13]. However, the real bodies in the nature cannot absorb all the incident power and they also radiate less power than the blackbody. These bodies are called gray body.

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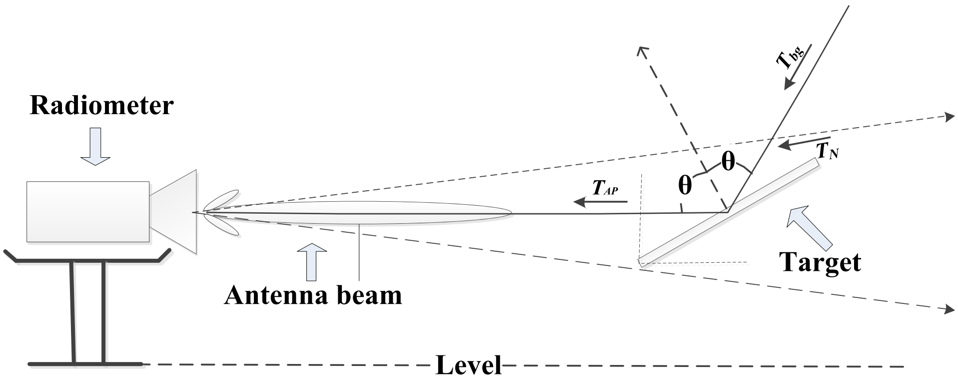

FIGURE 1. Sketch map of the traditional method and voltage method.

Since the BT of a gray body is smaller than that of a blackbody, the BT is smaller than physical temperature T_{ph}. The parameter relating both magnitudes is called the emissivity $e(\theta,\varphi)$

$$e(\theta, \phi) = \frac{T_B(\theta, \varphi)}{T_{ph}} \tag{1}$$

where, T_B is the directional emission BT, which depends on the direction (θ,φ).

Thermal radiation may be absorbed, reflected and transmitted through a surface. According to the conservation of energy, the following relationship exists among the three.

$$\alpha + \rho + \tau = 1 \tag{2}$$

Assuming that the target is in thermal equilibrium state, in this limit, the effective emissivity of a metal-coated dielectric surface is given by

$$e = \alpha = 1 - \rho \tag{3}$$

Ignoring sensor effects and transmission, the apparent temperature is formed by two parts, with one coming from the target and the other coming from the radiation of the background reflected by the target.

$$T_{AP} = e \cdot T_{ph} + (1 - e) \cdot T_{bg} \tag{4}$$

where, T_{AP} is the apparent temperature, T_{bg} is the radiation from the background, T_{ph} is the physical temperature of the target.

III. ERROR ANALYSIS OF TRADITIONAL METHOD

As shown in Fig.1, considering the antenna pattern, the measured BT T'_{Atg} of the target can be expressed as

$$T'_{Atg} = \frac{\iint\limits_{\Omega_1} T_{APtg} F_n(\theta, \varphi) d\Omega + \iint\limits_{4\pi-\Omega_1} T_N(\theta, \varphi) F_n(\theta, \varphi) d\Omega}{\iint\limits_{4\pi} F_n(\theta, \varphi) d\Omega} \tag{5}$$

where, T_{APtg} is the apparent temperature of the target, T_N is the radiometric temperature of the non-target area covered by the antenna beam, $F_n(\theta,\varphi)$ represents the normalized pattern of radiometer antenna, Ω_1 is the solid angle of the target area.

In the traditional method, T_{ph} is usually obtained by measuring the physical temperature of the target surface, and the results can be equated with the BT of blackbody at the same temperature. The relation can be expressed as

$$T_{ph} = \frac{\iint\limits_{4\pi} T_{APbb} F_n(\theta, \varphi) d\Omega}{\iint\limits_{4\pi} F_n(\theta, \varphi) d\Omega} \tag{6}$$

where, T_{APbb} is the apparent temperature of the blackbody.

In the traditional method, the emission BT of the background reflected by the target needs direct measurement, and the result can be expressed as

$$T'_{Abg} = \frac{\iint\limits_{\Omega_1} T_{APbg} F_n(\theta, \varphi) d\Omega + \iint\limits_{4\pi-\Omega_1} T'_N(\theta, \varphi) F_n(\theta, \varphi) d\Omega}{\iint\limits_{4\pi} F_n(\theta, \varphi) d\Omega} \tag{7}$$

where, T_{APbg} is the apparent temperature of the background.

Since background measurements and target measurements are not in the same area, the $T'_N(\theta,\varphi)$ and the $T_N(\theta,\varphi)$ are different. Connect (4)-(7), the emissivity can be expressed as

$$e = \left(\frac{T'_{Atg} - T'_{Abg}}{T_{ph} - T'_{Abg}}\right) \cdot A - B \tag{8}$$

A and B can be expressed as

$$A = \frac{T_{ph} - T'_{Abg}}{(T_{ph} - T'_{Abg}) - \iint\limits_{4\pi-\Omega_1} (T_{ph} - T'_N(\theta, \varphi)) F_n(\theta, \varphi) d\Omega} \tag{9}$$

$$B = \frac{\iint\limits_{4\pi-\Omega_1} (T_N(\theta, \varphi) - T'_N(\theta, \varphi)) F_n(\theta, \varphi) d\Omega}{(T_{ph} - T'_{Abg}) - \iint\limits_{4\pi-\Omega_1} (T_{ph} - T'_N(\theta, \varphi)) F_n(\theta, \varphi) d\Omega} \tag{10}$$

But, in the traditional method, the emissivity e is given as [11], [14]

$$e = \frac{T'_{Atg} - T'_{Abg}}{T_{ph} - T'_{Abg}} \tag{11}$$

Compare (8) with (11), the errors of traditional method relate to physical temperature, antenna pattern and ambient radiation,

IV. VOLTAGE METHOD

For isotropic targets, the effectiveness of the voltage method is based on the following three hypotheses:

1) The radiometer is a linear system;

2) The background environment remains unchanged during the measurement;

3) The calibrated metal plate has the same scattering spatial distribution with the target to be measured.

The above hypotheses are reasonable and can be realized. In voltage method, the unknown target, the metal plate and the blackbody are measured by radiometer respectively. Supposing that the sizes of these targets are consistent, and the targets are placed in the same position with the same observation angle, the measurement scene is shown in Fig.1. Then, the radiometric temperature of these targets can be expressed as

$$T'_{Atg} = \frac{\iint\limits_{\Omega_1} T_{APtg} F_n(\theta,\varphi) d\Omega + \iint\limits_{4\pi-\Omega_1} T_N(\theta,\varphi) F_n(\theta,\varphi) d\Omega}{\iint\limits_{4\pi} F_n(\theta,\varphi) d\Omega} \tag{12}$$

$$T'_{Amt} = \frac{\iint\limits_{\Omega_1} T_{APbg} F_n(\theta,\varphi) d\Omega + \iint\limits_{4\pi-\Omega_1} T_N(\theta,\varphi) F_n(\theta,\varphi) d\Omega}{\iint\limits_{4\pi} F_n(\theta,\varphi) d\Omega} \tag{13}$$

$$T'_{Abb} = \frac{\iint\limits_{\Omega_1} T_{APbb} F_n(\theta,\varphi) d\Omega + \iint\limits_{4\pi-\Omega_1} T_N(\theta,\varphi) F_n(\theta,\varphi) d\Omega}{\iint\limits_{4\pi} F_n(\theta,\varphi) d\Omega} \tag{14}$$

where, the scripts tg, mt, bb represent target, metal and blackbody respectively.

The emissivity of metal plate is approximated to 0, and the emissivity of artificial blackbody approximated to 1. Connecting (4) and (12)-(14), supposing that the blackbody surface and the target surface have the same physical temperature, then the emissivity of the unknown target can be given as

$$e = (T'_{Atg} - T'_{Amt}) \Big/ (T'_{Abb} - T'_{Amt}) \tag{15}$$

According to two-point calibration theory [15], (15) can be rewritten as

$$e = (V'_{tg} - V'_{mt}) \Big/ (V'_{bb} - V'_{mt}) \tag{16}$$

where, V'is the output voltage of radiometer.

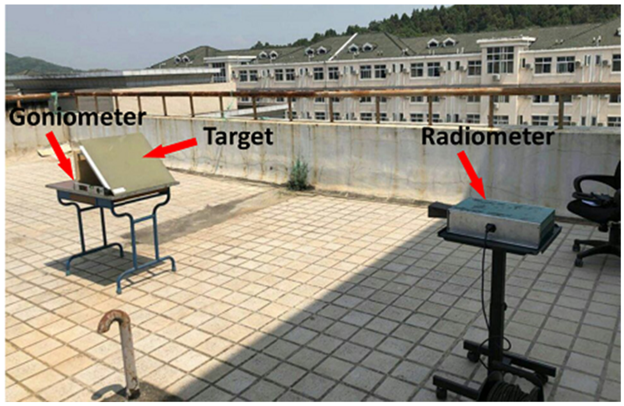

FIGURE 2. Experimental scene map of voltage method.

Compared with traditional method, the voltage method does not need to measure the radiation of background and the physical temperature of the targets' surface directly, and the errors arose due to that the antenna's main lobe and side lobe cannot be completely covered by the target can be eliminated in this method by measuring the blackbody and metal plate of the same size as the target sample. Furthermore, the traditional method needs to convert the measured voltage values to the BT through the calibration, and then calculate the emissivity, however, the voltage values can be used to calculate the emissivity directly in voltage method.

V. EXPERIMENTS

In order to verify the voltage method, measurement experiments are designed and conducted. Both voltage method and traditional method are tested. The experimental scene map is shown in Fig. 2.

In the experiment, the receiver is a Dick radiometer which works at 35 GHz with 400MHz bandwidth, 1.0 s integration time, and the radiometric sensitivity is 0.6 K. Two polarizations are measured by rotating radiometer. The target in this experiment is a metal plate coated with stealthy nano-materials and its surface can be considered as specular surface. Unknown target, metal plate and blackbody are measured at different angles successively in the experiment. The observation angles range from 20° to 60°, with 10° as an interval. All samples have a size of 50 cm × 50 cm. In order to verify the beam coverage problem mentioned in section 3, the radiation pattern of the radiometer antenna is simulated. Results show that the half power beam width of surface E (phi = 0) and surface H (phi = π /2) are 4.6° and 7.4° respectively.

The emissivity of the target was also measured in Shandong non-metallic Materials Research Institute by arch method [16]. Arch method is the most widely used method in reflectivity measurement, and the method was invented by the US Naval Research Laboratory. This method can reduce stray reflection outside the sample area using the time gate function of vector network analyzer (VNA).

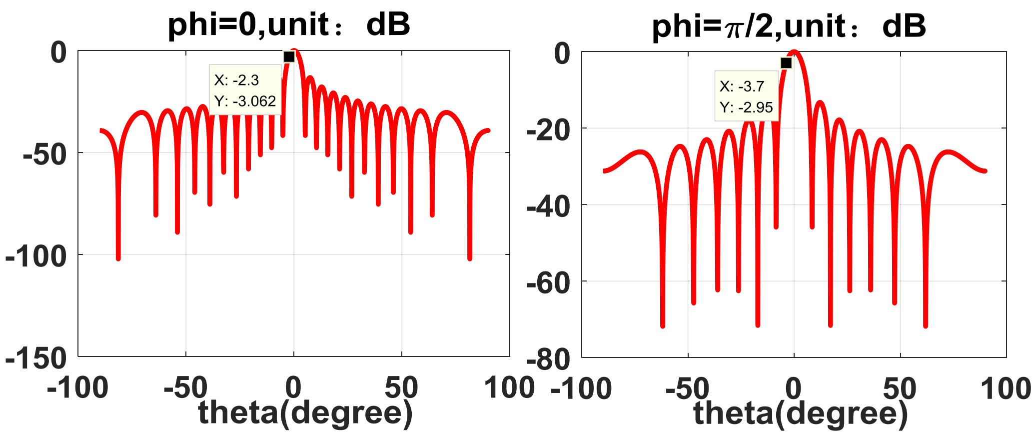

FIGURE 3. Radiation pattern of radiometer antenna.

TABLE 1. Measurement uncertainty (Uncertainty of blackbody emissivity, plate emissivity and temperature control are 0.01, 0.01 and 0.5K).

Parameter	e=0.2	e=0.5	e=0.8
Uncertainty of target measurement	0.001	0.0026	0.0041
Uncertainty of blackbody measurement	0.0022	0.0057	0.0092
Uncertainty of metal plate measurement	0.0122	0.0153	0.0184
Total uncertainty in emissivity	0.0124	0.0165	0.021

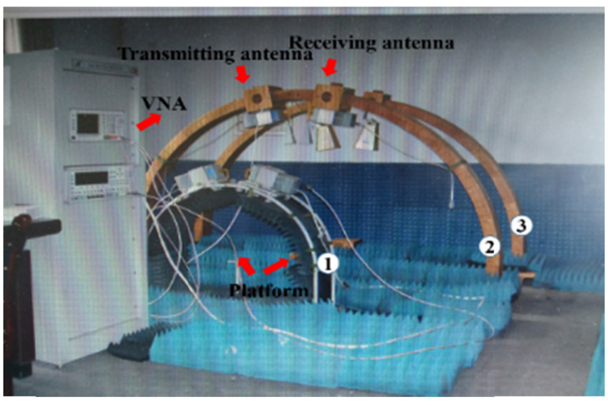

FIGURE 4. Experimental scene map of arch method.

The experiment scene of the arch method is shown in Fig. 4. The gate 1 works at 80 GHz ∼ 100 GHz, gate 2 works at 30 GHz ∼ 40 GHz, and the gate 3 works at 8 GHz ∼ 12 GHz. In this paper, we conduct the experiment with gate 2. Reflectivity of the target in different incident angles are measured by changing the position of the transmitting antennas and the receiving antennas on the bow frame, and then the corresponding emissivity is calculated using (3).

VI. RESULTS

The results are plotted in Fig. 5 and Fig. 6. As can be seen from Fig. 5, the voltage method has a higher precision than the traditional method. The results of arch method are used as the standard results. Fig. 6 plots the absolute errors of voltage method and traditional method. Experimental results demonstrate that the average absolute errors of voltage method are 0.00997 under horizontal polarization and 0.00845 under vertical polarization. The results are better than the traditional method which has a mean relative error of 0.06275 under horizontal polarization and 0.07428 under vertical polarization.

In theory, the errors of traditional method come from two aspects: one is that the main beam is not covered by the target fully, and the other is that there is stray power released by the side beam. Specifically, with the increase of the observation angle, the projection area of the target on the main beam of the radiometer antenna becomes smaller, and the beam receives more energy from the area beyond the target, so the errors of the emissivity become bigger.

VII. MEASUREMENT UNCERTAINTY

In voltage method, the blackbody is approximated to an ideal radiator, the metal plate is approximated to an ideal reflector, and the physical temperature of the blackbody is the same as that of the target to be measured. The target emissivity is obtained by measuring the target, the blackbody and the metal plate respectively. The uncertainty of the emissivity measurement is caused by such components as radiometer, temperatures of the sample and blackbody, ambient temperature, emissivity of the blackbody and the metal plate and so forth.

In this paper, the uncertainty of measurement due to temperature inconsistency and emissivity of blackbody and metal plate are analyzed. Assuming that the measurement is

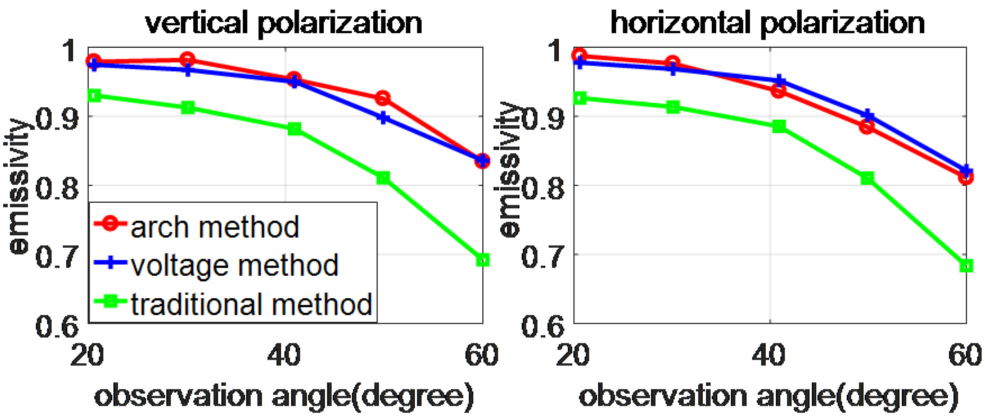

FIGURE 5. Comparison of the results between the three methods.

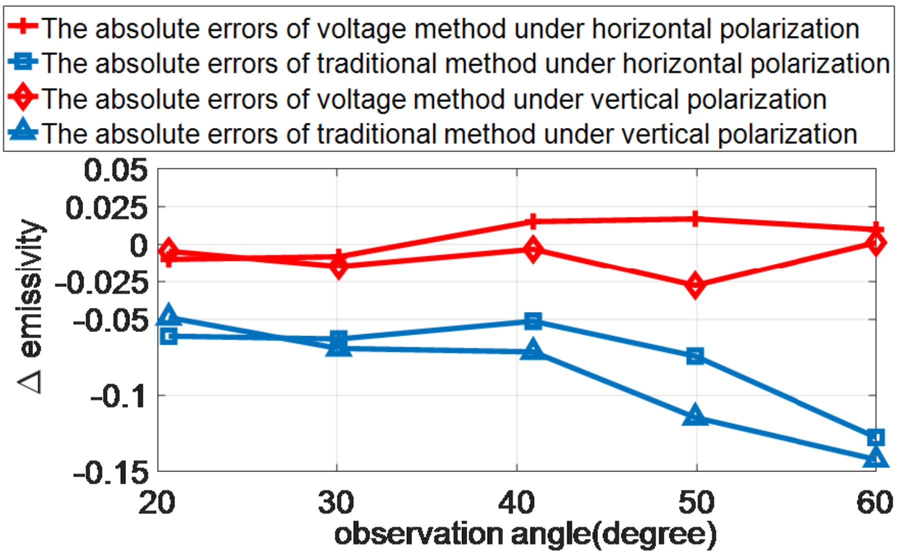

FIGURE 6. Comparison of the absolute errors.

TABLE 2. Measurement uncertainty (Uncertainty of blackbody emissivity, plate emissivity and temperature control are 0.001, 0.001 and 0.5K).

Parameter	e=0.2	e=0.5	e=0.8
Uncertainty of target measurement	0.001	0.0025	0.004
Uncertainty of blackbody measurement	0.001	0.0026	0.0018
Uncertainty of metal plate measurement	0.0012	0.0015	0.0018
Total uncertainty in emissivity	0.0018	0.0039	0.006

operated at room temperature of 300K, three sample emissivities have been taken into account: 0.2, 0.5 and 0.9. The uncertainty is calculated when the emissivity of the blackbody is 0.99 and 0.999, the emissivity of the metal plate is 0.01 and 0.001, and the temperature difference is 0.5K. The results are shown in Tab.1 and Tab.2.

VIII. CONCLUSION

This paper investigates the methods that use radiometer to measure emissivity of targets. The errors of traditional measurement method are discussed and appropriate formulas for error calculation are presented. On this basis, an improved method named voltage method for measuring the emissivity of flat targets' surface at microwave/ millimeter-wave bands is devoloped.

The improved method aims at eliminating the errors caused by the antenna pattern in traditional method. Contrast experiments are conducted, and the experimental results indicate that the voltage method performs well and improves the measurement accuracy greatly than the traditional method.

Therefore, the voltage method is potential in measuring emissivity of the target surface.

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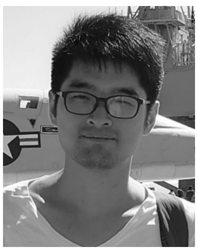

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