Numerical Analysis on the Emissivity Determination of Microwave Calibration Targets by Scattering Measurements

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***Abstract*—The calibration target is a vital instrument for calibrating the space-borne microwave radiometers. The calibration target is designed to be with a high emissivity close to 1, and its emissivity must be accurately determined before its practical usage. The emissivity of calibration target can be determined in the way of reflectivity measurement, in which the overall reflectivity has to be inferred based on the measured scattering in limited angular region. There are typical two setups in measuring the emissivity, one is the mono-static measurement and the other is the bi-static measurement. In this work, the authors discuss the remaining issues in the two measurement configurations, and report their recent progresses.**

Keywords—Microwave Calibration Targets, Emissivity, Mono-static Scattering, Bi-static Scattering, Scattering Measurement

I. INTRODUCTION

The microwave calibration target is a vital instrument to calibrate the space-borne radiometers on a satellite, by providing referencing brightness temperature radiation [1-3]. For such a purpose, the calibration target is designed to be with a high emissivity and low surface temperature gradient. Based on the Kirchhoff's law of thermal equilibrium, achieving a high emissivity is equivalent to realizing a low reflectivity. As a consequence, the calibration target is generally designed in shape of periodic array of coated sharp metal pyramids/cones, for low reflection in the microwave band [4-7].

As the calibration target is the referencing source for the quantitative microwave radiometer observations, its emissivity must be determined before functioning on board [2,3,7]. In practice, the emissivity is determined by finding the electromagnetic reflectivity, which is done by the scattering measurements [8-13], in a mono-static configuration or a bi-static configuration. By now, the required emissivity of calibration target has been risen to 0.999x for space-borne radiometer missions. It means that a reflectivity less than -30 dB has to be measured and examined correctly. There are two problems in the reflectivity measurement of a calibration target: First, a low reflectivity leads to the scattering very weak to be accurately captured; Second, the reflectivity is defined by the integration of scattering within the upper-space, while it is almost impossible to cover the whole angular region in practical measurements. After all, the reflectivity has to be inferred based on measured weak scattering at/in limited space positions/regions.

The first issue abovementioned has been a problem especially for the mono-static scattering configuration. By now it can be tackled by the space standing-wave methods[8-10]. The second issue, however, remains to be analyzed and concluded for both the mono-static and bi-static scattering measurement configurations. The general shape of calibration target is periodic coated pyramids/cones, that leads to the Floquet phenomenon in the scattering process from the calibration target [6,14-16], as will be explained latter. It is important to understand such a scattering property of calibration target in inferring its reflectivity based on limited measured scattering. In this work, the determination of reflectivity in both the mono-static and bi-static measurement configuration are to be discussed, with the consideration of the Floquet scattering properties. The rest of this paper include: the relationship between reflectivity and scattering, as well as the Floquet scattering properties of the calibration target is reviewed in chapter II, then the mono-static and bi-static configurations are addressed in chapter III and IV, finally conclusions are drawn in chapter V.

II. EMISSIVITY, REFLECTIVITY AND SCATTERING

A. Reflectivity and Scattering

Based on the Kirchhoff's law of thermal equilibrium, emissivity $e=\alpha=1-r$. Specifically, the emissivity of the calibration target at frequency f of polarization h or v toward the direction of (θ_i, φ_i) can be determined by the reflectivity to plane-wave illumination from (θ_i, φ_i) of h or v. Here, only consider the emissivity towards normal direction ($\theta_i = 0^\circ$ and

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$\varphi_i = 0°$). In this case, $e^h = e^v$, due to the structural symmetry of calibration targets. For the ease of demonstration, θ_i, φ_i and polarization *h* or *v* will be omitted in the rest of this paper.

In Fig. 1, the configuration of reflectivity determination of the calibration target is shown. The reflectivity is defined by the ratio of integrated scattered power to the intercepted illumination power. The total reflection can be obtained by either integrating far-field differential scattering coefficients in half space (Eq. (1)) or on any close surface around the targets (Eq. (2)). In both ways, it requires full scattering field distributions to fulfill the integration. However, in practical measurements, this requirement seems too difficult to be met.

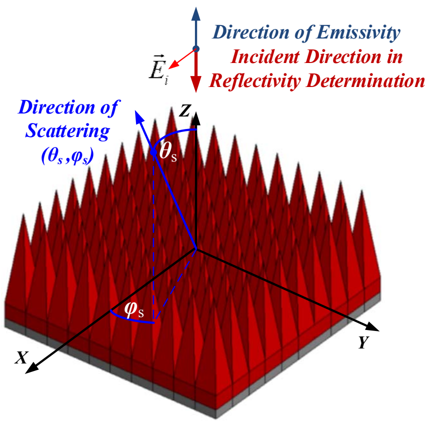

Fig. 1. Configuration of scattering from microwave calibration targets consisting of periodic coated sharp pyramids

$$r(f) = \frac{1}{4\pi}\iint_{2\pi} \gamma(f,\theta_s,\varphi_s)\sin\theta_s d\theta_s d\varphi_s \qquad (1)$$
$$\gamma(f,\theta_s,\varphi_s) = \frac{S(f,\theta_s,\varphi_s)4\pi}{P_{inc}(f)}$$

Where $S(f,\theta_s,\varphi_s)$ stands for the angular scattering power density towards (θ_s,φ_s) in far-field, while $\gamma(f,\theta_s,\varphi_s)$ stands for the differential scattering coefficients, the integration of which over space leads to the reflectivity, and P_{inc} is the intercepted illumination power by the calibration target.

$$r(f) = \frac{P_{refl}(f)}{P_{inc}(f)} = \frac{\frac{1}{2}\iint_{\Sigma} \mathrm{Re}(\vec{E}_s \times \vec{H}_s^* \cdot \hat{n})dS}{P_{inc}(f)} \qquad (2)$$

Where Σ stands for any aperture that covers the scattered power around the calibration target in the near-field region, and P_{refl} is the overall reflected/scattered power by the calibration target.

B. Floquet Scattering

As the calibration target shapes in a planar periodic structure, the Floquet scattering properties will be exhibited. This is due to the fact that in a plane wave illumination, the scattering from each unit will be coherently added up at some specific directions. Considering an normal illumination with a plane-wave phase pattern, there would be at least one additive scattering lobe at the mirrored direction in all frequency region, which is the basic Floquet mode or the backscattering lobe, and more scattering lobes will rise when the frequency is high enough so that $c/f = \lambda < p$ [6,14-16]. The angular positions of those scattering lobes can be found base on the Floquet mode theory as in Eq. (3), apparently only limited pairs of (*m*, *n*) can lead to actual scattering lobes (Satisfying $k_x^2+k_y^2<k_0^2$).

$$\begin{pmatrix} \sin\theta_s^{m,n}\cos\varphi_s^{m,n} \\ \sin\theta_s^{m,n}\sin\varphi_s^{m,n} \\ \cos\theta_s^{m,n} \end{pmatrix} = \begin{pmatrix} k_x^m / k_0 \\ k_y^n / k_0 \\ k_z^{m,n} / k_0 \end{pmatrix} = \begin{pmatrix} m\cdot\lambda/p \\ n\cdot\lambda/p \\ \sqrt{1-(m^2+n^2)\cdot(\lambda/p)^2} \end{pmatrix}, \qquad (3)$$
$$m,n = -\infty...0..1..\infty$$

Here, the k_x, k_y, k_z are the wave numbers towards the *X*, *Y*, and *Z* directions, respectively. And ($\theta_s^{m,n}$, $\varphi_s^{m,n}$) is the propagation direction of the (*m*, *n*) order Floquet lobe in the spherical coordinate system.

The Floquet theory indicates that the scattering power from the calibration target will be focused in a number of scattering lobes, also the total scattering power will be distributed among those lobes. This is the fact must be considered in measuring the reflectivity when frequency is large enough so that scattering lobes with ($m\neq0$, $n\neq0$) exist.

III. Mono-Static Measurement Configuration

For scattering measurement, the mono-static configuration is the most general setup. It can be achieved in the compact antenna test range (CATR), or in the near-field range with a focused aperture antenna. The weak scattering from the calibration target can be captured by using the space standing-wave method [8,10], and Gu et al proposed a further refinement with the consideration of propagation attenuation when using a small aperture antenna as the T/R [9].

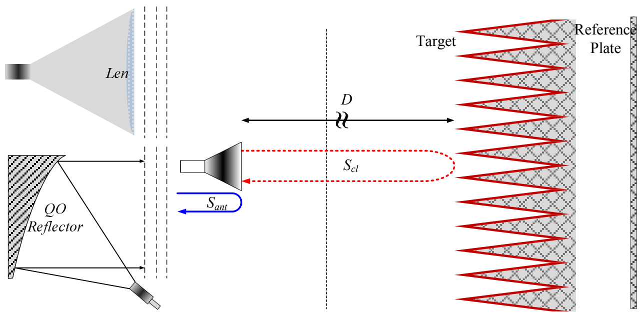

Fig. 2. Configuration of mono-static reflectivity measurement for microwave calibration target

In the mono-static measurement configuration of the calibration target, it should be noted that after the calibration of measured scattering with metal plate or other calibrators, one actually obtain the backscattering reflectivity. That can be defined as the ratio of scattering power within the backscattering lobe (the basic Floquet mode) to the total intercepted illumination power. Clearly, a compensation factor is necessary to obtain the total reflectivity, in the high frequency region.

$$r = r_{backscattering} \cdot C_g \qquad (4)$$

The authors has been conducting simulation works to numerically determine the C_g by periodic FDTD method. It is important that a quantitative value or ramge of C_g can be concluded for the typical and practical calibration target structures. For the simple structure of uniformly coated pyramids, the concluded C_g is about 10~13dB [13], and it is important that the computed C_g show convergence as the frequency keep rising up. Our results also show that the structure of coated cones leads to a more complex C_g variation. Meanwhile, it is been proven that the tapered coating, layered coating and bottom edge cut pyramid/cones give better low-reflectivity performance in designing calibration targets. The simulation works for quantitatively concluding the C_g continue, and are being performed for a more systematic conclusion for the mono-static reflectivity measurement on calibration target.

IV. Bi-Static Measurement Configuration

The bi-static measurement configuration leads to more measured scattering information from the calibration target than the mono-static scattering measurement. In the bi-static configuration, the transmitting and receiving antenna are separated therefore the measurement sensitivity for weak scattering is much better than that in the mono-static configuration. Also, it is important that in the high frequency region, more than one scattering lobe can be covered by scanned the angular region. The angular scanning along θ_s may reach a good balance between the accuracy and efficiency in measuring the reflectivity. Facility with both the θ_s and φ_s scanning function are being developed in the NSSC/CSSAR, CAS, for a national standard in measuring the emissivity of calibration targets. With the measured data by both the θ_s and φ_s scanning, the authors would be more supported in validating theoretical and numerical methods and results, and more importantly, in better understanding the scattering properties from calibration targets. Finally, the findings learned from the θ_s and φ_s scanned data, will be used in refining the measurement data processing techniques conducted in the more efficient θ_s scanning measurement.

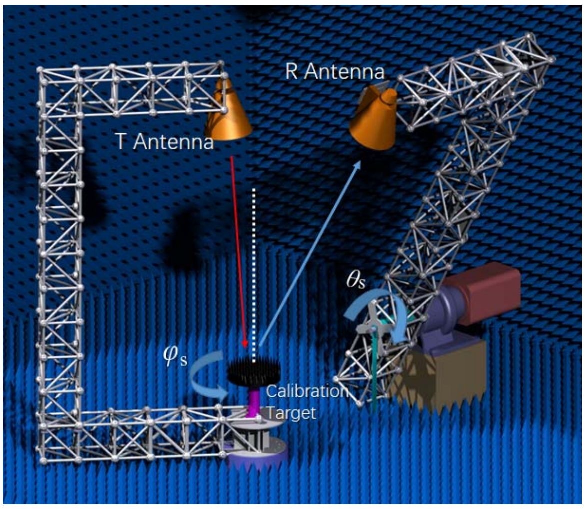

Fig. 3. Standard testing facility being developed in NSSC/CSSAR, CAS, for the emissivity/reflectivity determination of calibration targets.

In the bi-static measurement of calibration target, reference target is also necessary for calibrating the measured scattering amplitude. However, it is also desired that the scattering from the reference target can be used in inferring the reflectivity of calibration target. The simplest treatment as the comparison method, is shown in Eq. (5).

$$r \approx \frac{\int S_{blackbody}(\theta_s, 0)\sin(\theta_s)d\theta_s}{\int S_{ref}(\theta_s, 0)\sin(\theta_s)d\theta_s} \qquad (5)$$

Where $S_{blackbody}$ is the measured angular scattering power distribution from the calibration target, and S_{ref} stands for the measured data from the reference target.

Researches has been done on this topic [8, 12, 14-16], and some important conclusions have been found out:

(1) Relatively large aperture antennas with focusing ability at the target under test is more favorable than antennas of small aperture such as probes. That is because the near-field effect must be eliminated in the test, as it has been found to be disturbing and problematic in determining the reflectivity. Furthermore, a preferred illumination effect can be observed in Fig. 4 as a reference, which is with edge-tapered magnitude and flat phase distributions over the calibration target aperture.

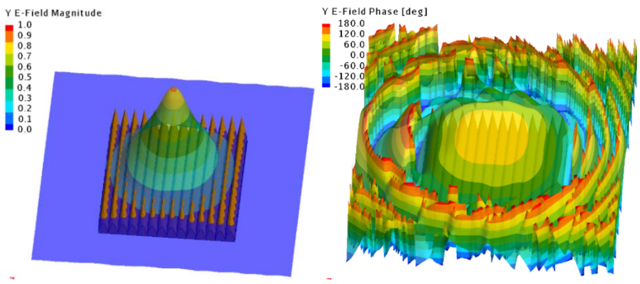

Fig. 4. Preferred antenna illumination on the calibration target under test in the scattering measurement.

(2) For the reference target selection, it has been found that the metal plate generally used in the reflectivity measurement is not suitable for the calibration target, because of their distinct scattering properties especially in the high frequency region. It is desired that the reference target can be with the same Floquet scattering properties as the target to be tested. The bare pyramids/cones array without absorptive coating may be a good candidate. However, the authors have found that, even with the same angular positions of Floquet scattering lobes, the scattering power distribution of bare pyramid array differs notably to that of coated pyramid. In this routine, efforts should be made to adjust the geometry of each unit of the reference target, for achieving a scattering distribution pattern close to that of the calibration target. However, the latter one is yet to be concluded and may vary according to different type of unit structure.

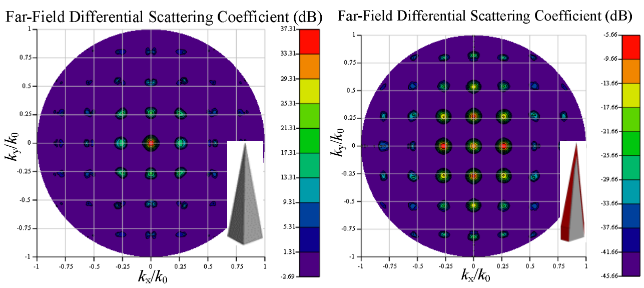

Fig. 5. Angular scattering distribution from bare pyramid array and coated pyramid array. (@ 89GHz, p = 12.5mm)

Apparently, accurate processing the measured scattering into using Eq. (5) requires a proper reference target, and designing of the reference target requires information of calibration target scattering properties. That can be obtained and concluded by a variety of numerical studies, considering different structural type, coating type, and so on, hence requires a lot of works.

As an alternative, one may determine the power carries by each measured scattering lobes by the bi-static scattering in the θ_s scanning and used these power values to fit those in unmeasured lobes, then sum them up for the reflectivity. The authors call this routine as lobe fitting method. This is a 1D to 2D data extraction and also requires information obtained by numerical studies. However, the conclusion for this method by numerical studies is apparently easier to be got than that for designing reference target to use Eq. (5), and the error analysis will be more straightforward.

V. CONCLUSIONS

In this work, the remaining difficulties in the reflectivity /emissivity measurement of microwave calibration target are discussed. Specifically, the mono-static and bi-static scattering measurement configuration are addressed. For the mono-static configuration, the compensation factor C_g is important in inferring the total reflectivity. For the bi-static configuration, the data processing method is focused on. The comparison method with a reference target is analyzed with detailed discussions, and a good alternative approach to get the total reflectivity is proposed. To further obtain systematic and quantitative conclusions, a variety of numerical studies are required, and results of those will be presented in following works.

REFERENCES

[1] H. Yang, F. Weng, L. Lv, N. Lu, G. Liu, M. Bai, Q. Qian, J. He, H. Xu, "The FengYun-3 microwave radiation imager on-orbit verification", *IEEE Trans. Geosci. Remote Sens.*, 49(11): 4452-4560, 2011.

[2] Z.-z Wang, J. Li, S. Zhang, and Y. Li, "Prelaunch calibration of microwave humidity sounder on China's FY-3A", *IEEE Geosci. Remote Sens. Lett.*, 8(1):29-33, 2011.

[3] F. Nian, Y.-j Yang, Y.-m Chen, D.-z Xu, W. Wang, "Recent progress on space-borne microwave sounder pre-launch calibration technologies in China", *Journal System Engineering Electronics*. 19(4): 643-650, 2008.

[4] J. Randa, A. E. Cox, D. K. Walker, "Proposed Development of a National Standard for Microwave Brightness Temperature", *IEEE IGARSS 2006*, DOI: 10.1109/IGARSS.2006.1025

[5] D. Houtz, D. K. Walker, D. Z. Gu, "Progress towards a NIST Microwave Brightness Temperature Standard for Remote Sensing", *2014 84th ARFTG Microwave Measurement Conference*, December 2014, DOI: 10.1109/ARFTG.2014.7013422

[6] S. Sandeep, A. J. Gasiewski, "Electromagnetic Analysis of Radiometer Calibration Targets Using Dispersive 3D FDTD," *IEEE Trans. on Antennas Propagat.*, 60(6): 2821-2828, 2012.

[7] D. Xia, M. Bai, and M. Jin, "Effects of Coating Material Properties on the Wideband Reflectivity Performance of Microwave Calibration Targets" *IEEE Trans. on Antennas Propagat.*, 65(9): 4909-4913, 2017.

[8] C.-y Chen, F. Li, Y.-j Yang, Y.-m Chen, "Emissivity measurement study on wide aperture microwave radiator", *IEEE Proc. ICMMT*, 914-917, 21-24 April 2008.

[9] D.-z Gu, D. Houtz, J. Randa, D. K. Walker, "Reflectivity study of microwave blackbody target", *IEEE Trans. Geosci. Remote Sens.,* 49(9): 3443-3451, 2011.

[10] A. Schröder, A. Murk, R. Wylde, K. Jacob, K. Pike, M. Winser, M. B. Pujades, and V. Kangas, "Electromagnetic Design of Calibration Targets for MetOp-SG Microwave Instruments, " *IEEE Trans. Terahertz Sci., Tech.*, 7(6): 677-785, 2017

[11] Z.-p Li, *Optimization for Microwave Radiometer Calibration Load and Study on Emissivity Accuracy Measurement Method*, ph.D dissertation, Beihang university, 2010.

[12] D. Liu, K. Liu, M. Jin, Z. Li, and J. Miao, "Simulation Analysis of the Effect of Measured Parameters on the Emissivity Estimation of Calibration Load in Bistatic Reflection Measurement", *PIER*, 125:327-341, 2012.

[13] Q. Gao, Y. Tao, C. Jing, M. Jin, D. Xia, and M. Bai, "Analysis on the Floquet Scattering Lobes from Microwave Calibration Targets", *PIERB*, 73: 147-161, 2017.

[14] J.-h Wang, J.-g Miao, Y.-j Yang, Y.-m Chen, "Scattering property and emissivity of a periodic pyramid array covered with absorbing material", *IEEE Trans. Antennas Propagat.*, 56(8): 2656-2663, 2008

[15] M. Jin, M. Bai, j-g Miao, "Emissivity study of the array shaped blackbody in the microwave band", *Acta Phys. Sin.*, 61(16): 164211, 2012.

[16] M. Jin, *The Scattering Modeling and Emissivity Study of the Periodic Conical Calibration Load for Microwave Radiometers*, ph.D dissertation, Beihang university, 2013.