ON STUDY OF ERROR SOURCES IN MICROWAVE THERMAL VACUUM NON-LINEARITY TEST AND ON-ORBIT VERIFICATION

1.Hu Yang, Member, IEEE, 2.Ninghai Sun, 2.Quanhua Liu, 3.R.Vincent Leslie, 4.Edward Kim,
5.Cheng-Hsuan Lyu, 6.Matthew Sammons, 7.James Feuntes,

1. UMD/CISESS, College Park, U.S
2. NESDIS/STAR, College Park, U.S
3. MIT-LL, Lexington, U.S
4. NASA/GSFC, Greenbelt, U.S
5. IMSG NASA/GESTAR, U.S
6. NASA GSFC/Fibertek, Inc, U.S
7. NGES, Azusa, US

ABSTRACT

For the on-orbit calibration of passive microwave radiometers, instrument non-linearity is a major error source, causing a scene-temperature-dependent error if not being properly corrected. non-linearity results from the intrinsic feature of the square-law detector and amplifiers used in total-power microwave radiometers, and can only be accurately characterized through the ground-based Thermal Vacuum Test (TVAC). The ground-based non-linearity characterization is then used in the calibration algorithm to attempt to remove this error source. Evaluation results for current operational microwave-sounding instruments show that the magnitude of the non-linearity error varies from channel to channel and from instrument to instrument, with maximum changes of several tenths of kelvins to several kelvins. While the different responses of the detector and amplifier may explain the non-linearity differences in different instruments, errors in TVAC tests could also increase the uncertainty in the non-linearity assessment. Therefore, accurate knowledge of error sources in the TVAC test and their corrections are important for a reliable and accurate non-linearity measurement. In this paper, major error sources in the TVAC test are studied and identified for the NOAA-20 Advanced Technology Microwave Sounder. Correction methods are developed by combining the pre-launch TVAC test and post-launch deep-space-scan test data sets. An on-orbit evaluation method is also proposed to validate the ground-measured instrument non-linearity.

Index Terms— non-linearity, TVAC Error Source, NOAA-20 ATMS, On-orbit Evaluation

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1. INTRODUCTION

For total-power microwave-sounding radiometers, onboard calibration is achieved by periodically observing the cold space and an internal blackbody target. Calibration measurements accurately determine the so-called radiometer transfer function that relates the measured digitized output (i.e., counts) to the radiance. The radiometric calibration is derived as follows [1]:

$$R = R_c + (R_w - R_c)\left(\frac{C_s - \overline{C_c}}{\overline{C_w} - \overline{C_c}}\right) + Q, \qquad (1)$$

where R_w and R_c are the radiances of warm and cold calibration targets corresponding to the warm and cold target temperatures (T_w and T_c), respectively, $\overline{C_w}$ and $\overline{C_c}$ are the mean warm and cold counts within the calibration window, respectively, and C_s is the scene count. The non-linearity parameter, Q, in Eq. (1) was estimated using data sets derived from the pre-launch thermal vacuum (TVAC) test. In the TVAC test, the scene temperature is typically measured between 83 K and 330 K. However, for on-orbit calibration, the cold calibration reference is usually set to deep space. Thus, the non-linearity value must be estimated by extrapolating TVAC data to temperature range between 2.73 K cold-space and the on-orbit internal warm-load temperature. In general, the non-linearity parameter Q can be expressed as a function of the free parameter μ:

$$Q = \Delta R = \mu \cdot (R_w - R_c)^2 x(x-1), \qquad (2)$$

where R_w and R_c are the radiances of warm and cold calibration targets, and x is the normalized scene counts, i.e., $x = \frac{C_s - C_c}{C_s - C_w}$. From Eq. (2), the accuracy of μ largely depends on knowledge of ΔR, which is the difference between the scene radiance reference truth R_s and the linear calibrated scene target radiance R_b:

$$\Delta R = R_s - R_b. \quad (3)$$

While R_s can be calculated from the scene temperature T_s, which is directly measured by the platinum resistance thermometers (PRTs) in the TVAC test's variable calibration targets (var CTEs), its accuracy largely depends on the PRT measurement error and the temperature distribution homogeneity in the targets. R_b is derived from cold and internal calibration targets (fixed CTE) through the two-point linear calibration equation. Its accuracy not only depends on the PRT measurement accuracy and the temperature gradient in the fixed CTE, but also depends on other error sources in the calibration process, such as system noise and thermal dissipation in antenna reflectors. In the following sections, the impact of the temperature gradients and reflector thermal emission in var CTE targets will be studied. Investigated are their impacts on non-linearity accuracy. Section 2 examines antenna reflector thermal dissipation and its correction. Section 3 presents the correction for the temperature gradient in CTE targets. Section 4 describes a proposed method for on-orbit instrument non-linearity evaluation. Section 5 presents a discussion and conclusions.

2. CORRECTION FOR REFLECTOR THERMAL EMISSION IN TVAC DATA

Due to the coating material used, the rotating plane reflector is not a perfect reflector and has its own thermal emission. For the non-linearity error in the TVAC test, the impact of the antenna reflector thermal emission is always mixed with incoming target temperature. To study the impacts of the temperature gradient on the CTE target, the antenna thermal emission must be firstly corrected from T_b. Previous studies show that the antenna reflector emission is angle dependent, and its emissivity can be accurately calculated from a physical model and post-launch deep-space-scan observations. With accurate knowledge of the reflector emissivity and the reflector physical temperature, the reflector emission can be corrected from radiances of cold and warm calibration targets in the TVAC test [2]:

For Q_V channels,

$$\Delta R_x = \epsilon_h \left(R_{rfl} - R_x\right) + \left(R_{rfl} - R_x\right) \times (\epsilon_v - \epsilon_h) \times \sin^2 \theta_x. \quad (4)$$

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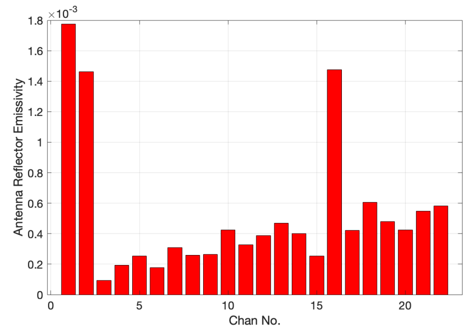

Fig. 1: NOAA-20 Advanced Technology Microwave Sounder antenna reflector emissivities derived from the on-orbit pitch-maneuver test.

In Eq. (4) and Eq. (5), ΔR_x is the contribution of reflector thermal emission when the reflector pointing to different targets, such as cold space, internal targets, or the Earth scene(ΔR_c , ΔR_w, or ΔR_s. The subscripts c, w, and s stand for the fixed cold and warm calibration targets, and the scene target respectively). Radiance can be converted to T_b using the inverse Planck function. Taking into consideration the antenna reflector emission, the corrected cold and warm target T_bs are calculated as $T_c^{'} = T_c + \Delta T_c$ and $T_w^{'} = T_w + \Delta T_w$. When the scene temperature is set to equal the cold-target temperature in the TVAC test, instrument non-linearity can be ignored, and the total T_b coming in front of the antenna can be calculated from the corrected cold and warm target T_bs using the following linear calibration equation:

$$T_s{'} = T_w + (T_w - T_c)\left(\frac{C_s - \overline{C_w}}{\overline{C_w} - \overline{C_c}}\right). \quad (6)$$

The reflector-emission-corrected scene target T_b can then be derived as follows:

$$T_s = \frac{(T_s^{'} - T_{rfl} \cdot S_a)}{(1 - S_a)}, \quad (7)$$

where S_a is the antenna reflector emission correction term for the scene target at scan angle θ_s. For Q_V channels, $S_a = \epsilon_h + (\epsilon_v - \epsilon_h) \cdot \sin^2 \theta_s$. For Q_H channels, $S_a = \epsilon_h + (\epsilon_v - \epsilon_h) \cdot \cos^2 \theta_s$. In this study, the antenna reflector emissivities ϵ_h and ϵ_v derived from the post-launch deep-space-scan test are used to correct TVAC data. Figure 1 shows NOAA-20 antenna reflector emissivities derived from deep-space observations during the on-orbit pitch-maneuver test. From the intrinsic feature of quadratic non-linearity response it is known that, if there are not other error sources, the calibration error should follow a quadratic curve, which will reach the maximum at temperature around 160K and converged to zero at cold and warm end. As shown in Figure

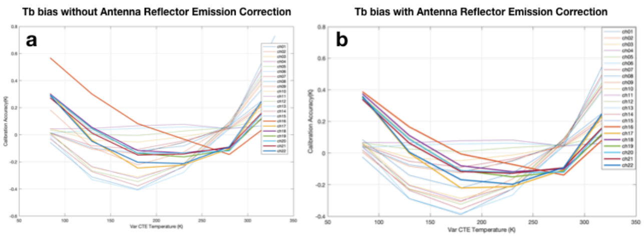

Fig. 2: Antenna reflector emission correction for TVAC data.

2a, without any corrections, the original calibration errors across all channels in NOAA-20 Advanced Technology Microwaver Sounder (ATMS) TVAC test did show strong scene temperature dependent feature following a quadratic curve, but they did not converged to zero at cold end around 84K and warm end around 280K. It indicates that in the TVAC test, except for non-linearity error, there are another error source in calibration process that needs to be corrected. From our previous study it is already known that antenna reflector thermal emission is a an important error source in ATMS calibration process, its magnitude depends on the detection frequency, scan angle, as well as the temperature difference between antenna reflector and observing scene[2]. As shown in Figure 2b, for channels with larger reflector emissivity such as channel 16 (with central frequency of 89GHz), the reflector emission correction is significant and can be as large as 0.2K. It is also observed that after reflector emission correction, the residual calibration errors clustered into two distinct groups: KKa/V bands and W/G bands. Considering that in TVAC test, in addition to the internal calibration target for warm end, there are two sets of external blackbody targets being used for calibration. One is fixed and variable target for KKa/V bands and the other is for W/G bands. The clustering feature in calibration error is not a coincidence, it indicates that after antenna reflector emission correction, the residual calibration error might be related to the specific external targets in TVAC test used for different channels. The details will be discussed in next section.

3. CORRECTION FOR TEMPERATURE GRADIENTS IN CTE TARGETS

After reflection emission being corrected from calibrated radiance of var CTEs, the error in the scene reference temperature can be studied. During the TVAC test, the target temperature needs to be stabilized at the preset temperature point. For a ideal black-body target, temperatures are distributed homogeneously over the entire target when it reaches a stable status [3]. But in reality, due to the imperfect design and thermal conduction inside the TVAC chamber, there could be a temperature gradient as large as 0.5 to 1 K across the target surface. Figure 3 shows temperature gradients in the fixed and var CTE targets used for NOAA-20 Advanced Technology Microwave Sounder TVAC tests. After correcting for the antenna reflector emission, the bias-corrected target temperature can be calculated as the weighted average of each single PRT temperature measurement:

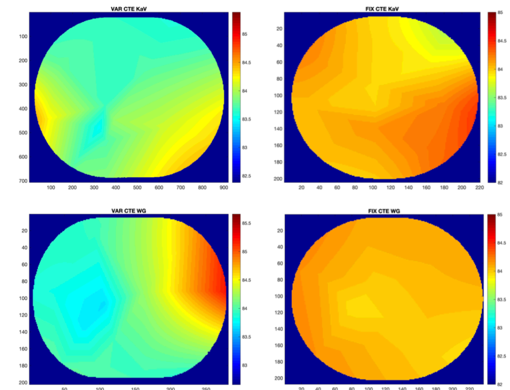

Fig. 3: Temperature gradients across NOAA-20 Advanced Technology Microwave Sounder TVAC CTE targets.

$$T_s^{corr} = \sum_{i=1}^{n}(w_i \cdot PRT_i). \quad (8)$$

In Eq. (8), PRT_i is the temperature measurement from the $i_t h$ PRT inside the CTE target. The corresponding weight w_i can be derived from an optimum regression algorithm:

$$\min(\sum(T_s - w_i \cdot PRT_i)) \quad (9)$$

The constraint $\sum w_i = 1$ should be applied. Figure 4 shows the calibration accuracy of TVAC data after correcting for the temperature gradient. After applying the correction, greatly reduced are errors in the reference target temperature, and cold-target biases converge to zero for all channels. Some residual errors still existed in warm-end, which may due to the coupling between warm target and the reflected environment radiation. It should be noted that after the correction, a cleaner non-linearity curve can be derived for on-orbit calibration.

4. ON-ORBIT EVALUATION OF INSTRUMENT NON-LINEARITY

Figure 2 shows that the peak in non-linearity is usually located at a T_s of around 160 K. Therefore, the evaluation of instrument non-linearity needs a wide dynamic range of T_s measurements so that the non-linearity

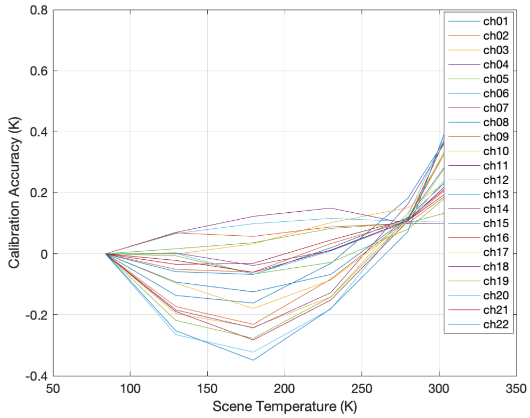

Fig. 4: Impact of the CTE temperature gradient correction on the NOAA-20 Advanced Technology Microwave Sounder TVAC calibration accuracy.

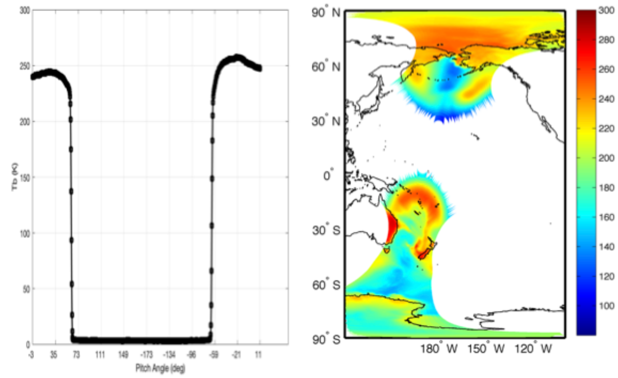

Fig. 5: Temperature profile at nadir of a scan in NOAA-20 ATMS pitch-maneuver observations (left panel) and location of the NOAA-20 pitch-maneuver operation (right panel).

curve can be determined. For this reason, characterization of non-linearity is largely depends on ground TVAC test, with no standard technique for measuring non-linearity on orbit. For the NOAA-20 Advanced Technology Microwave Sounder (ATMS), a series of intense on-orbit calibration/validation tests were carried out shortly after the satellite launch. Among them was the pitch-maneuver test where the satellite platform was pitched over completely 360° while the instrument was in normal-scan mode. Figure 5 shows the location of a NOAA-20 pitch-maneuver operation and the T_b profile at field-of-view 48. With the change in pitch angle of the satellite platform, the ATMS antenna beam scans across the boundary between the earth and outer space. T_b changes from 280 K when the main beam is completely inside the earth to around 3 K when it is in cold space. The wide dynamic range of T_s measurements provides an opportunity in future to evaluate instrument non-linearity when it's on orbit.

5. SUMMARY AND CONCLUSIONS

Investigated in this study is the accuracy of instrument non-linearity measured in a TVAC test for the NOAA-20 ATMS. Temperature gradients in CTE targets and antenna reflector emission are two major error sources having significant impacts on the non-linearity measurement accuracy if they are not properly corrected. By combining post-launch and ground test results, the antenna reflector emissions in fixed and var CTE targets in the TVAC tests can be corrected using the antenna emissivity derived from post-launch deep-space-scan data. By comparing the T_s truth and the measured PRT temperature, the weights of each PRT measurement inside the CTE target can be reassigned, and the bias in T_s can be corrected. After correcting for the temperature gradient and antenna reflector emission, the bias in cold and warm target temperatures converge to nearly 0 K. An on-orbit non-linearity evaluation method is proposed to validate the non-linearity measured in the TVAC test. Although the study focused on the NOAA-20 ATMS instrument, results obtained here are expected to benefit other similar microwave-sounding radiometers.

6. REFERENCES

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