Calibration Procedure of a Microwave Total-Power Radiometer

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***Abstract*—A total-power radiometer built in combination with a beacon receiver is being used for low-level attenuation measurements. This experimental receiver was built to measure atmospheric propagation impairments, using the ITALSAT satellite 50-GHz signal. The radiometer is mainly used to provide the reference level for the beacon measurements. Its precision should be better than ±3 K, for low attenuation levels, in order to have 0.1-dB accuracy in the attenuation measurements. A suitable calibration procedure is described in this letter.**

***Index Terms*—Millimeter wave propagation, radiometer calibration, radiometry.**

I. Introduction

Ground-based microwave radiometers are used in many applications, one of which is atmospheric attenuation estimation. Radiometric measurements are frequently carried out in conjunction with slant-path propagation experiments, in order to establish a reference level for the received satellite signal and to estimate low-level atmospheric attenuation. Of all the various types of radiometers, the "total-power" radiometer is the simplest to implement [1]. However, it is the most gain sensitive. A calibration procedure is needed to ensure the required accuracy.

The Radiocommunication Group of the Polytechnic University of Madrid has constructed an experimental beacon receiver, which includes a built-in total-power radiometer, to participate in the ITALSAT F1 satellite propagation experiment in millimetric waves [2]. The antenna and RF hardware are shared by the beacon receiver and the radiometer so that both have the same system noise temperature and antenna pattern. Thus, while obtaining reliable measurements [3], the construction cost of the system is lower than in the case of separate hardware.

II. Experimental Setup

The radiometer, which operates in the 50 GHz band, consists of an antenna pointed toward the Italsat satellite (40° elevation) and RF equipment, composed of outdoor and indoor blocks (see Fig. 1).

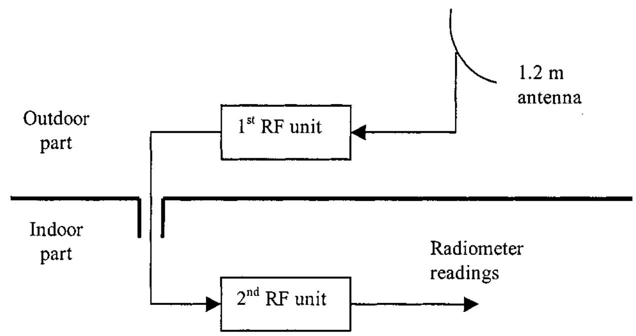

Fig. 1. Block diagram of the receiving system.

While the outdoor unit is subjected to significant temperature variations, the indoor unit operates under more stable conditions thanks to the building protection and air-conditioning system, which works five days a week from Monday to Friday. Two temperature sensors have been installed to record temperature variations; one of them is situated near the 1st IF amplifier, in the outdoor unit, and the other is close to the radiometer diode detector, in the indoor unit. Those are the most temperature sensitive elements in both RF units. The temperature data are recorded and registered every 10 minutes.

III. Calibration Procedure

The main purpose of any radiometry experiment is to obtain the brightness temperature at a specific frequency band. The relationship between this temperature, T_b [K], and the voltage measurement obtained with the radiometer, V_{rad} [V], is given by

$$V_{rad} = k \cdot B \cdot g \cdot (\eta_l T_b + (1-\eta_l) \cdot T_{ssp} + T_{rx}) = k \cdot B \cdot g \cdot T_t \text{ [V]} \quad (1)$$

where $k = 1.38 \cdot 10^{-23}$ J/K is the Boltzmann constant, B [Hz] is the IF noise bandwidth of the receiver, g is the total receiver gain, T_{ssp} [K] is the noise temperature of the antenna's sidelobes, T_{rx} [K] is the receiver noise temperature, and T_t [K] is the total input noise temperature, that includes all the contributions. η_l is the sky-coupling coefficient. Starting from this formula, the proposed calibration method can be explained by the following steps.

A. Receiver Noise Temperature Determination

A calibration process is necessary to get this value. This process consists of applying two loads to the antenna-input [1, 4]; a "cold load," that is an absorbent material cooled by liquid nitrogen down to 77.4 K, and a "hot load," using the same material at ambient temperature, which, in our case, was 294.5 K. With a load, the radiometer voltage becomes $V_{rad} = kBg(T_{rx} + T_l)$, where T_l [K] is the load temperature. Two measurements with different load temperatures are sufficient to obtain the receiver noise temperature, which yields in our case 491.3 K.

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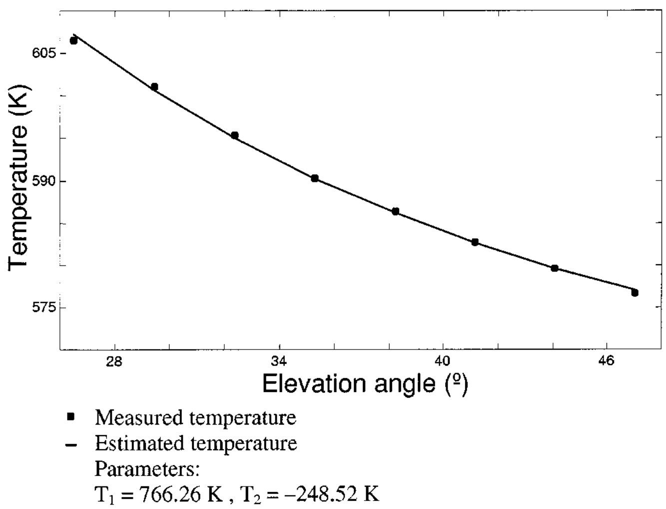

Fig. 2. Example of sky-tipping measurements.

B. Antenna Sidelobes Noise Temperature Determination

The antenna receives noise from various sources. The main lobe is intended to detect the brightness temperature of the atmosphere at 50 GHz. However, the sidelobes may capture atmospheric or surface radiation at the same frequency increasing the measured temperature. This increase in temperature is regarded as a sidelobes noise temperature T_{ssp} and can be obtained through sky-tipping measurements (tip curve calibration) once the receiver noise temperature is known.

The sky-tipping process consists of an elevation scan in which the radiometer measures the total input noise temperature, T_t [K], at chosen intervals (see an example in Fig. 2). The tip-curve is fitted with the following expression:

$$T_t = T_1 + T_2 \cdot e^{-(\tau/\sin\theta)} [\text{K}] \quad (2)$$

where τ is the zenith attenuation, θ [rad] is the elevation angle and T_1 [K] and T_2 [K] are given by

$$T_1 = (1-\eta_l) \cdot T_{ssp} + \eta_l \cdot T_{mr} + T_{rx} \ [\text{K}] \quad (3)$$

$$T_2 = \eta_l \cdot (T_o - T_{mr}) \ [\text{K}] \quad (4)$$

where T_{mr} [K] is the effective medium temperature (which can be estimated from the surface temperature) and $T_o = 2.73$ K is the cosmic background temperature.

Zenith attenuation is estimated using radiosonde data applied to the method described in Recommendation ITU-R P. 676-4 [5], obtaining a value of τ of around 0.2.

A process of iterations, focused on the minimization of the error between the experimental tip-plot and the estimation equation (2), was carried out to get the values of T_1 and T_2. To obtain consistent values, sky-tipping calibrations are routinely performed when the atmosphere is stable (stability conditions are tested with radiosonde data). The mean value of the sidelobes noise contribution obtained from the described procedure is $(1-\eta_l)T_{ssp} = 30$ K.

C. Receiver Gain Estimation

The receiver gain should be characterized with an appropriate expression to estimate its value. To find out its dependencies, correlation processes have been carried out whose results show a strong relationship between the receiver gain and the temperature of different parts of the receiving station (outdoor and indoor blocks). Therefore, the receiver gain G [dB] can be described by the following equation:

$$G = G_o + k_1 \cdot T_{in} + k_2 \cdot T_{out} \ [\text{dB}] \quad (5)$$

where G_0 [dB] is a constant term, T_{in} [K] is the temperature of the indoor unit, T_{out} [K] is the outdoor temperature and k_1 [dB/K] and k_2 [dB/K] are fitting parameters.

Hence, G_0, k_1 and k_2 must be determined to estimate the receiver gain. In order to obtain these parameters, a simple method has been used: a "hot load" at ambient temperature is inserted in front of the antenna horn for a long period of time (several days); the gain is obtained and, through an iteration process, the parameters are fixed in order to minimize the total error between the experimental and the estimated gain, as shown in Fig. 3.

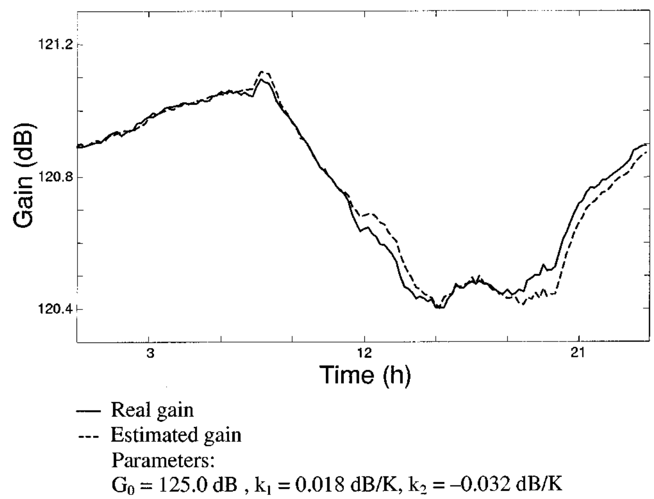

Fig. 3. G_0, k_1, and k_2 obtained through a fitting process.

TABLE I
FITTING PARAMETERS TO ESTIMATE RECEIVER GAIN

PERIOD OF TIME	G_0 [dB]	K_1 [dB/K]	K_2 [dB/K]
Monday – Friday	118.7	0.039	–0.032
Saturday – Sunday	125.0	0.018	–0.032

The indoor unit is exposed to various conditions during the week (at weekends the air-conditioning system is not working) which therefore leads to the set of parameters included in Table I. Both values of $k1$ are very different. This is probably due to the high temperature stability in week days. Typically, indoor temperature varies less than 3–4 K in a 24-hour period. For this reason, the estimation of $k1$ is less accurate in these conditions, but the error is also less important. Moreover, the parameter G_0 is recalculated for each day by means of short calibrations as shown in Fig. 4. Three short calibrations of about 30 s in duration using a hot load are carried out every day. In this way, a diurnal correction is made in order to minimize the error of the estimated gain.

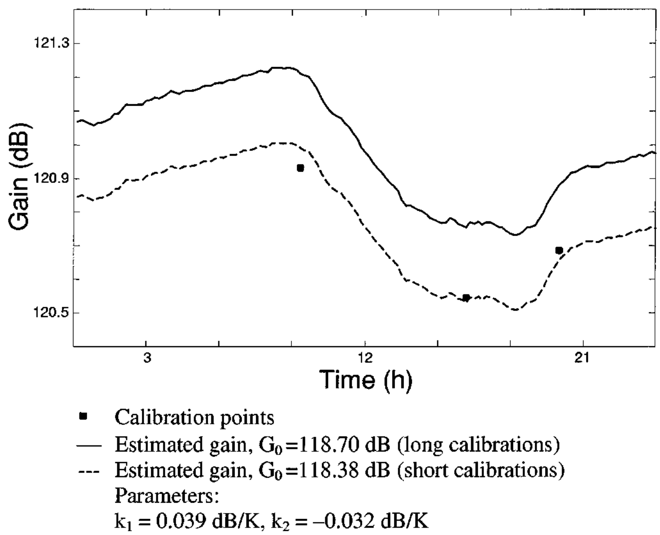

Fig. 4. G_0 recalculation and gain adjustment with short calibrations.

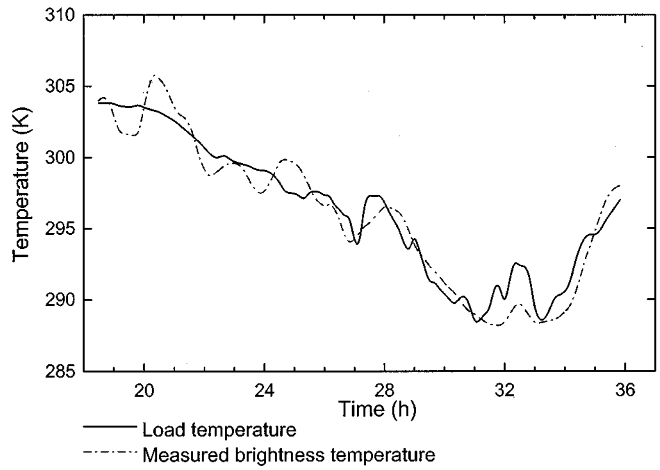

Fig. 5. Load temperature and measured brightness temperature comparison.

The radiometer precision can be tested by means of the measurements taken when the "hot load" is inserted for several days. Fig. 5 shows a comparison of the load temperature and the brightness temperature, measured with the radiometer. The calibration parameters have been obtained from the measurements carried out the previous day. The difference is within an interval of ± 3 K. Under normal operating conditions, the measured brightness temperature is in the order of 100 K (for low atmospheric attenuation). From (1), it can be derived that the radiometer precision (in K) is slightly better when the measured brightness temperature is smaller, provided that the gain estimation errors are similar.

IV. Conclusion

A simple method has been presented to calibrate experimental total-power radiometer measurements. The radiometer gain is strongly correlated with the temperatures of the indoor and outdoor RF blocks. Through the use of long and short "hot load" calibrations, accurate estimations of the gain can be obtained. Sky-tipping and "cold load" calibrations are also needed to estimate the remaining parameters.

This radiometer was constructed in combination with a beacon receiver to measure the atmospheric attenuation with 0.1-dB accuracy. Its measurements are used as reference for the beacon data, in clear-sky and corresponding low attenuation levels (in the order of 2 dB). In these conditions, the radiometer precision should be better than 3 K. The described calibration procedure was designed to obtain this precision with a relatively simple radiometer configuration.

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