

# Experimental Study of a Low-Cost Radiometer for Hostile Scenarios

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**Abstract**—Noncontact temperature measurements in industrial scenarios present great variety of difficulties (dust, vapor...). In this work, the authors study the use of a low-cost microwave power radiometer to measure the temperature of hot metal plate during its cooling with water. Two different radiometers, centred at different frequency bands, have been experimentally considered. The radiometers have been surrounded with a metal box to reduce undesirable radiation. Several experiments have been carried out, showing the ability of these radiometers to detect the cooling of the plates. A recalibration of the radiometer gain can be done to compensate the gain variation of the circuitry of the radiometers.

## 1. INTRODUCTION

Temperature monitoring in industry is a necessity to keep the safety and product quality. Contact measurement can be done using thermocouples or optical fibers, but in many cases, this process can damage either product or the measurement probe. In that case, remote temperature sensing is desirable, for example, using pyrometers that detect the thermal radiation of a sample in the infrared band. However, these systems are not suitable for industrial hostile situations, with vapor or dust. The small particles, which form this scenario, absorb or scatter the infrared radiation, leading to a high attenuation. To solve this problem, microwave radiometers are used.

The thermal noise radiation power at microwave frequencies is directly proportional to its temperature, according to the Rayleigh-Jeans law. This spontaneous radiation can be detected by a radiometer. This kind of devices has been widely studied [1] and used in many applications, from radioastronomy [2] to breast cancer detection [3, 4] or industrial processes [5, 6]. However, these devices are bulky and expensive to incorporate a large number of them as sensors in a production chain. So the authors have chosen a total power radiometer [7, 8] instead of a classical Dicke radiometer, in spite of losing some accuracy.

The main objective of this work is to study the measurement of temperature of hot metal plate during its cooling with water. In this process, a great amount of vapor is produced, creating a hostile scenario for measurement. To the authors' knowledge, non-contact measurements of temperature of hot plates have not been carried out. This work investigates the possibilities of using total power radiometer for this application.

## 2. EXPERIMENTAL SET-UP

### 2.1. Basic Radiometer Overview

The function of a radiometer is to measure the power of microwave radiation. In general, this radiation comes from the thermal radiation of any material with a temperature above 0 K. The radiometer collects

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the

available power  $P_i$  within a bandwidth,  $B$ . This power can be modelled, following the Rayleigh-Jeans's Law as:

$$P_i = k \cdot B \cdot T_A \quad (1)$$

where  $k$  is the Boltzmann's constant and  $T_A$  the antenna temperature, which takes into account of the physical temperature,  $T$ , and emissivity,  $\varepsilon$ , of the materials around the antenna and the antenna radiation field of view. For a planar screen at a distance  $d$  from the antenna,  $T_A$  can be expressed as

$$T_A = \frac{\iint \varepsilon(x, y) T(x, y) C(x, y) dx dy}{\iint C(x, y) dx dy} \quad (2)$$

where  $C(x, y)$  is a function proportional of the square of the electromagnetic near-field of the antenna at a distance  $d$ .

The radiometer amplifies ( $G$ ) the received thermal noise although some noise is added, increasing the apparent temperature in an amount of  $T_N$  and giving an output power:

$$P_i = k \cdot B \cdot G \cdot (T_A + T_N) \quad (3)$$

A block diagram and a picture of the implemented total power radiometer are shown in Fig. 1. A rectangular horn antenna supplies the noise power to a Low Noise Block (LNB). Two different LNBS have been used, one working at X-band and the other in Ka-band. The characteristics of these devices are summarized in Table 1. The LNBS amplify the thermal noise signal and deliver it in an intermediate frequency band. A diode square-law detector converts the RF signal in a DC signal that is integrated in a lowpass filter.

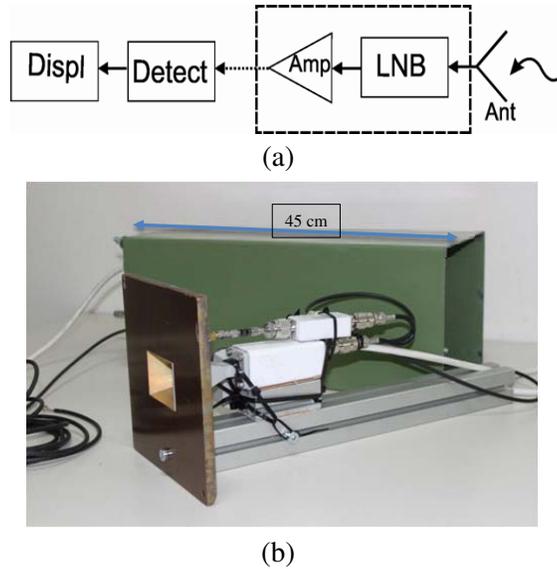
**Table 1.** characteristics of the used LNBS.

Specification	X-BAND LNB	KA-BAND LNB
Antenna Gain	10 dB	15 dB
<i>LNB Gain</i>	60 dB	55 dB
Input frequencies	12.25–12.75 GHz	18.20–19.20 GHz
Output frequencies	950–1450 MHz	950–1950 MHz
<i>Noise Figure</i>	0.7–0.9 dB	1.3 dB

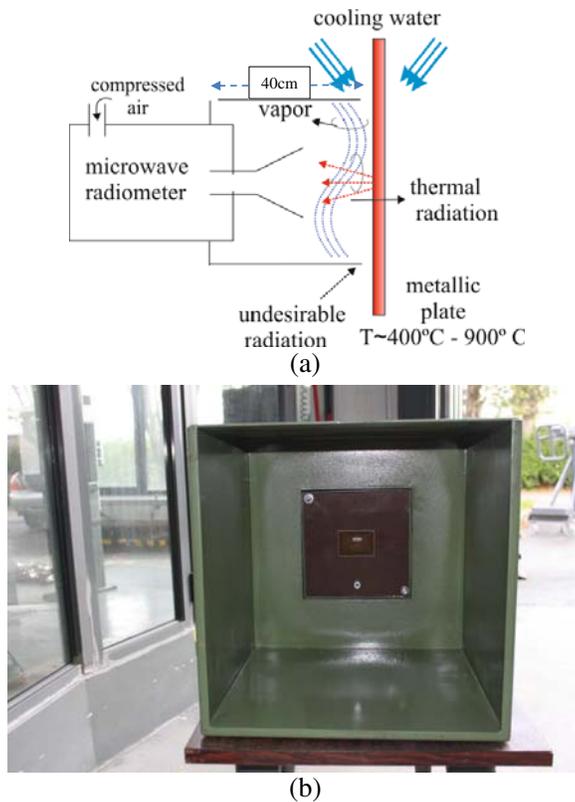
## 2.2. Experimental Hostile Scenario

The radiometer is thought to measure the temperature of metal plates during its cooling with water from around 950°C to ambient temperature in assembly line where a great amount of vapor is present. To reproduce this scenario, a rectangular 0.4 m × 0.4 m metal plate is heated in an industrial oven to around 900°C. This plate is taken out and can be cooled with air or with water, generating vapor. The plate is placed in front of the radiometer, and a thermocouple is connected to the plate to validate the radiometer measurement. The emitted heat of the plate warms the radiometer, so the prototype is enclosed and cooled with compressed air to maintain the radiometer temperature at 20°C, avoiding gain drift due to temperature variations.

Another problem found in the preliminary experiments was the low thermal emissivity of metals [9]. However, the measured plate is slightly oxidized. This oxide increases the emissivity of the plate. Also the metal plate reflects the presence of the electromagnetic radiation due to ambient thermal noise radiation and can damage the radiometer measurement. To block this undesirable radiation, the radiometer has been surrounded by a cubic metal box of 0.4 m of side size. The final experimental scenario is sketched in Fig. 2.



**Figure 1.** (a) Sketch of a low-cost power radiometer. (b) Photograph of the designed power radiometer.



**Figure 2.** (a) Sketch of a power radiometer with the metal plate to reduce the undesirable radiation. (b) Photograph of the prototype.

### 3. EXPERIMENTAL RESULTS

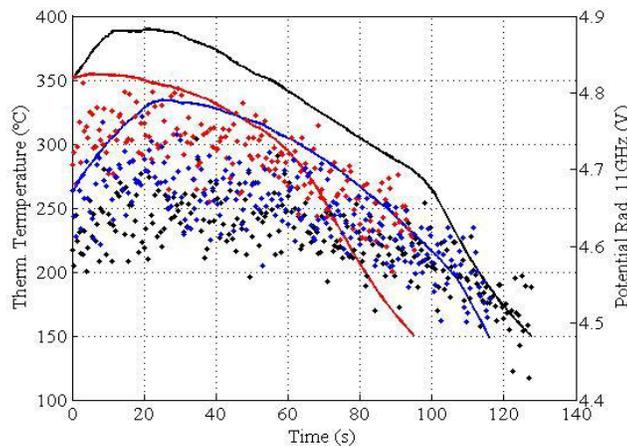
Several measurements have been carried out to characterize the behavior of the radiometer, using different experimental set-ups in the facilities of Arcelor-Mittal Research Centre in Avilés, Spain. The

first experiment tries to study the repeatability in semi-hostile scenario. In this case, only the exterior face of the metal plate is wet for cooling, so less vapor is produced. This experiment has been performed three times for the X-band radiometer and others three times for the Ka-band radiometer. A picture of the experiment is shown in Fig. 3.



**Figure 3.** Picture of one of the performed experiment. A stream of water is poured onto the sheet metal, measured by the radiometer.

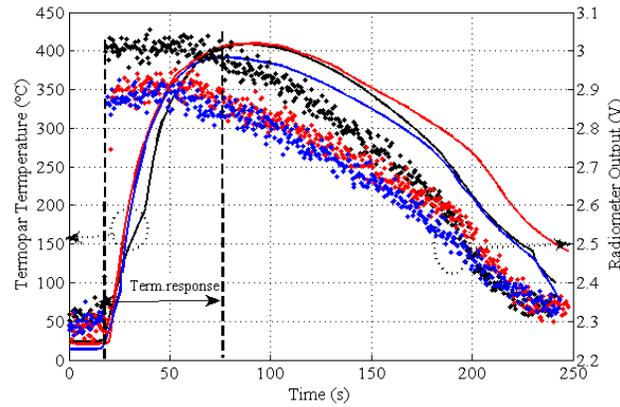
The results for the X-band radiometer are plotted in Fig. 4. Although the radiometer can detect the hot metal plate, with a clear voltage increase, a significant drift spoils the measurement. The researchers assume that this drift is due to the antenna's low gain.



**Figure 4.** Results of the experiments 1–3 with the X-band radiometer. The thermocouple output is plotted with continuous lines and the radiometer output, with dotted lines.

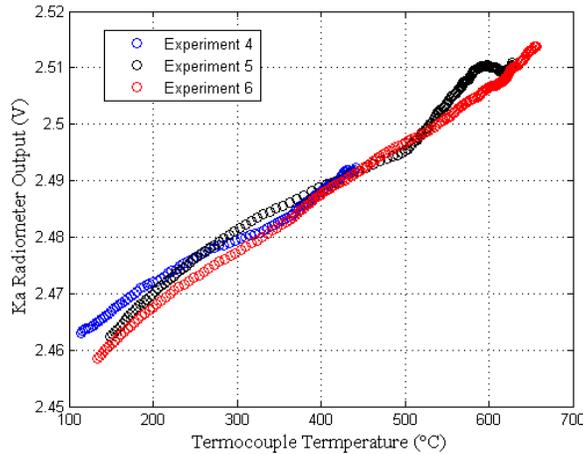
Same experiment has been repeated with the Ka-Band radiometer, increasing the antenna gain. These measurements (Fig. 5) show that the radiometer immediately detects the presence of the hot metal plate (dotted lines), whereas the thermocouple needs more than 50 s to detect the metal plate. During this time, the metal plate is cooled by air, so a light slope in the radiometer potential is observed. When the thermocouple is stabilized, the cooling with water begins, producing vapor, and the temperature of the metal plate falls quickly. In the three experiments, the slopes of the thermocouple and radiometer are similar.

A calibration curve can be drawn. The total power radiometer suffers from an initial gain drift. This problem has been reported, and several papers deal with it. In our case, the cooling is fast enough, and the radiometer subsystems are refrigerated with compressed air, so the internal temperature system



**Figure 5.** Results of the experiments 4–6 with the Ka-band radiometer. The thermocouple output is plotted with continuous lines and the radiometer output, with dotted lines.

is unaffected. We assume that the gain remains constant during the measurement. Only an initial point temperature-potential is needed. In our case, this point is at high temperature ( $T = 620^{\circ}\text{C}$  — potential 2.51 V). Using the data of the first experiments, the relations between the radiometer potential and the thermocouple temperature are plotted in Fig. 6. In the three cases, a linear slope can be seen, with an error of around  $20^{\circ}\text{C}$ .



**Figure 6.** Calibration curve for experiments 4–6 with the Ka-band radiometer.

Similar experiments have been carried out but with cooling water in both faces of the metal plate (Figs. 7–8) for both radiometers. A faster cooling is produced, so the radiometers have a smaller internal temperature drift than in the first experiment. The radiometers detect the hot metal plate in 3 seconds, while the thermocouple needs more than 20 seconds. The Ka-band presents a better sensitivity than the X-band one. For this radiometer, a calibration curve is drawn (Fig. 9) with an accuracy around  $20^{\circ}\text{C}$ . These results maintain the accuracy up to around  $150^{\circ}$ . From this temperature to ambient temperature, not only vapor is present, but liquid water drops are formed in random points of the metal plate. The water has a different temperature and emissivity than the metal plate, and the random distribution makes a great variations in the thermal radiation, making an accurate radiometer measurement impossible.

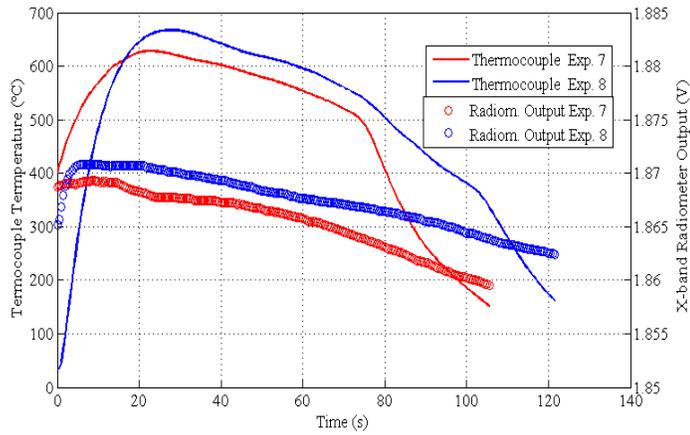


Figure 7. Results of the experiments 7 (red)–8 (blue) with the X-band radiometer.

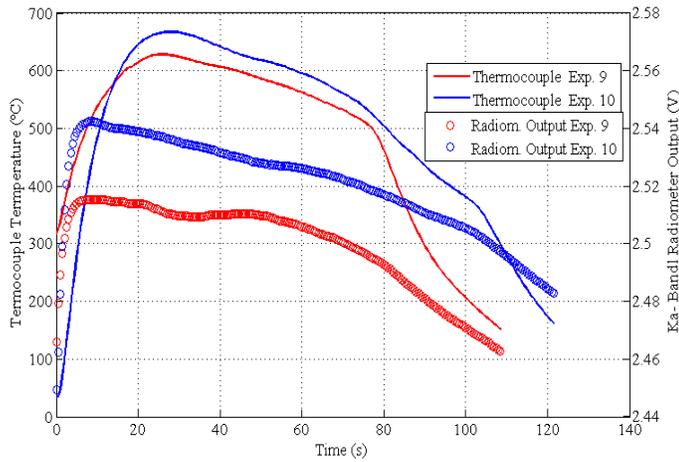


Figure 8. Results of the experiments 9 (red)–10 (blue) with the Ka-band radiometer.

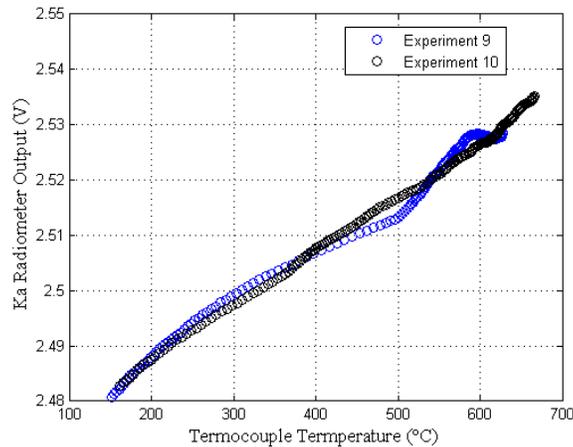


Figure 9. Calibration curve for the experiments 9–10 with the Ka-band radiometer.

#### 4. CONCLUSIONS

Thermal microwave radiation measurement can be a good solution to temperature measurement in industrial scenarios, where vapor or dust is present. In this work, two total power radiometers, one at X-band and the other at Ka-band, have been studied to measure the temperature of a metal plate when cooling with water. A metal box has been added to the radiometer to reduce undesirable radiation coming from reflections. The experiments show that both radiometers detect the drop of the temperature of the metal plate. However, the Ka-band radiometer is more stable, and only gain variation appears, typical of power radiometers. The voltage drift can be compensated to obtain a calibration curve between temperature and output voltage, up to 150°C.

#### ACKNOWLEDGMENT

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