A low-cost differential radiometer that detects the human microwave emissions

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The implementations of radiometers that use a low noise block (LNB) as a reception front-end to demonstrate human emission of microwave electromagnetic fields generally follow the typical diagram of the Total Power receiver shown in Figure 1. They sense between 11GHz and 12GHz – the radio frequency band of an LNB.

Literature has described very simple implementations with single receivers, and further architectural and calibration improvements have also been made. In one such previous system (Elettronica e Telecomunicazioni, Centro Ricerche e Innovazione Tecnologica RAI, year LV, no. 2, pp. 7-14, Aug. 2006), at environment temperature T_{Env} = 300K, the receiver's noise temperature T_R corresponds to the LNB's noise figure (NF) of 0.3dB:

$$T_R = T_{Env}\left(10^{\frac{NF}{10}} - 1\right) = 21\text{K} \qquad (1)$$

Therefore, considering the wall at a temperature T_{Wall} = 300K, the system temperature T_{Sys} is:

$$T_{Sys} = T_R + \eta T_{Wall} \cong 200\ \text{K} \qquad (2)$$

with $\eta \cong 0.6$ being the antenna's electrical efficiency (measured by the producer).

The minimum detectable temperature ΔT_{min} (or sensitivity) is:

$$\Delta T_{min} = \frac{T_{Sys}}{\sqrt{B \cdot \tau}} = 6.32 \cdot 10^{-3}\text{K} \qquad (3)$$

where receiver bandwidth B is about 1GHz, and $\tau \cong 1$s is the time constant of the integrator that follows the detector.

The system must detect a theoretical observing system's temperature $\Delta T \cong 7$K, which represents the difference between the surface temperature of the body in the antenna's beam (307K) and the wall's temperature (about 300K). In operating conditions, only a portion of the body is exposed to the antenna's beam, which makes the actual ΔT below 7K. The sensitivity is in any case considered much lower than the real value of ΔT, and the system is expected to detect a body at about 307K.

Once in operation, this system works well, though it requires frequent manual adjustments of the offset circuit during the day to maintain near zero the signal measured in absence of a person in front of the antenna. In fact, it was observed that where the system was installed, temperature variations of the wall that the paraboloid "sees" can even reach 10K over 24 hours, widely overcoming the observing system's ΔT.

In addition, the LNB's gain has a great instability and the detector's characteristics depend on the ambient temperature. This predictable behaviour is mainly due to the high gain of the amplification chain (about 100dB), necessary to produce the output levels required by the ADC: small changes in the electronic components' physical temperature lead to large gain variations. This drawback, which in these specific conditions makes an operator indispensable, is analysed here in order to find a solution.

T&M carried out on a single-receiver system

During the tests and measurements performed to quantify the equipment's stability in normal operation, the LNB was pointed at a constant-temperature wall so that measurements were not affected by changes in the wall's surface temperature "seen" by the LNB. The equipment was kept on for a few hours and, every 30 minutes, the temperature inside the container as well as the detector's output voltage were measured; see Figures 2 and 3. Figure 4 shows the detector's output voltage as a function of the container's temperature. From these measurements we determine that the stabilisation time is too long for "ready to use". Moreover, once in operation and after stabilisation, the system needs frequent realignments (every 30 minutes).

It was shown that the output voltage variations depend not only on thermal drift of the detector circuit (expected to be small because it is temperature compensated), but also on that of the amplifiers, including those in the LNB.

Figure 1: Block diagram of a single-receiver system

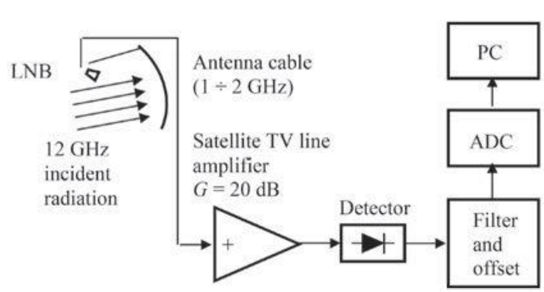


Figure 2: Graph of the temperature inside the receiver as a function of time (ambient temperature is 22.5°C)

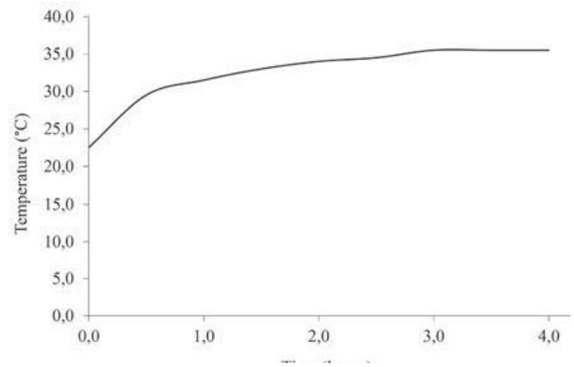


Figure 3: Graph of the detector's output voltage as a function of time (ambient temperature is 22.5°C)

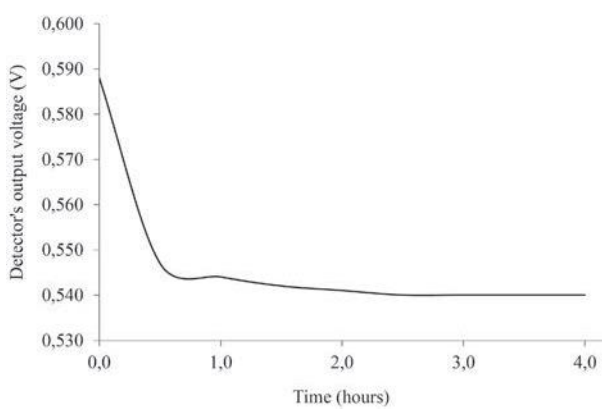
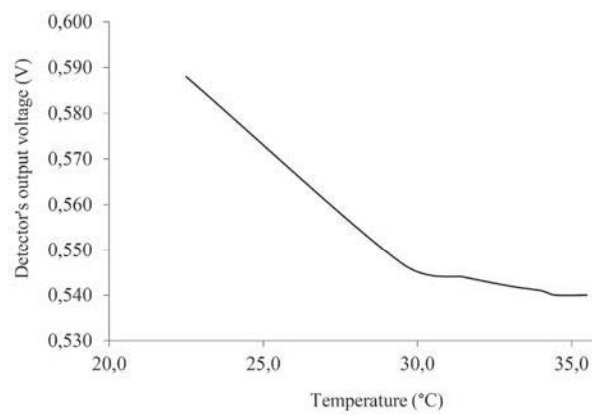


Figure 4: Detector output voltage as a function of the container's temperature



Improving the receiver's temperature stability

To improve temperature stability, the following solutions were considered:

1. Compensation of each block in the receiver: this requires temperature characterisation and compensation of each block; the total drift is approximately the sum of the individual drifts.

2. Entire system temperature compensation: this solution requires temperature characterisation of the amplification chain and detector, as a single device. We could use a temperature linear transducer (e.g. AD592), whose output voltage (which is temperature-dependent) is sent to a non-linear amplification network that approximates the system's response, and then sent to a simple differential amplifier. In this option, tuning is slow and difficult and the power-up time is equal to the stabilisation time of the slowest device.

3. Thermal stabilisation of the entire system using a digital proportional integral derivative (PID) controller. This solution is quite simple, using software tools such as LabVIEW for development and fine tuning. Unfortunately, power-up time is still about an hour.

There's also the "Dicke Receiver" and other solutions, but none show significant improvements in system stability, yet produce greater noise caused by harmonics resulting from beating between the chopper and line frequencies. These harmonics were found to be difficult to filter, either with analogue or digital techniques.

A logarithmic amplifier in place of the detector was also considered; see Figure 5. We used the AD8313.

The theoretical difference of received power between a person being absent or present in front of the paraboloid is about 0.12dBm. In real situations this difference is smaller because the target is located in the near-field zone (whereas the setup is at the far-field zone, at a distance of 5m or more from the paraboloid), so the antenna doesn't resolve the person but also intercepts the back wall. Considering an optimistic value of 0.1dBm, at the logarithmic amplifier's output there would be 0.1 x 18 = 1.8mV (at 1.9GHz the AD8313 datasheet indicates a typical "slope" of about 18mV/dB); therefore, to have a 4V excursion at the ADC input, a gain of about 2200 is necessary. If the goal is to comply with adequate stability margins, this will be too high. Our experimental results confirmed the theoretical predictions.

Figure 5: Use of a logarithmic amplifier in place of the detector

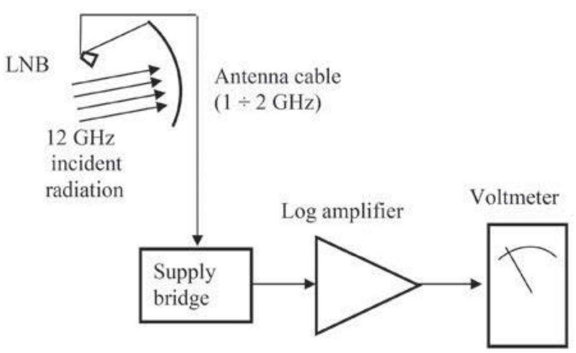
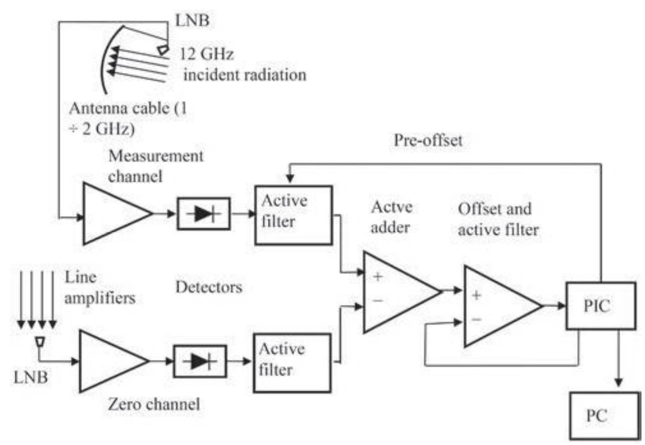


Figure 6: Double receiver system



The adopted solution

Because in our application the system must detect a person who enters the antenna beam, it is possible to consider an alternative approach consisting of subtracting the long period integrated value at the instantaneous signal; that way the receiver will only be sensitive to quick variations. The solution, achievable digitally, doesn't require components characterisation – the only choice is that of integration time; the sensitivity to the impulsive noise can be eliminated by inserting a time window decider.

The visualisation of the field's time evolution, however, will appear distorted if the visitor remains in front of the paraboloid for a long time. Moreover, by using this solution it is not possible to offset the quick variations in ambient temperature due to airflows (caused, for example, by opening a door or a window).

Taking all options into consideration, as well as the low cost of the components, it was decided to implement a "double" receiver, consisting of two same receiving systems; see Figure 6.

The first, which for simplicity we call the "measurement channel", receives the signal coming from the LNB mounted in the paraboloid's focus, with a beam that intercepts the back wall or the person moving in front of the antenna. The second, or "zero channel", receives the signal coming from the LNB pointed toward the ceiling. The signal from the zero channel is subtracted from that of the measurement channel. In this way, signal variations due to gains instability (assuming the termperature coefficients of the two amplification chains are identical) and temperature range of the back wall are deleted.

The place where it's easiest to compare the measurement and zero signals is just after the detection circuit. In this section we can operate with signals that are already at low frequency, avoiding complex and difficult modifications of the RF components, the line amplifier and the LNB – modifications that would be required if the comparison were made at earlier, higher-frequency stages.

It's clear that the greater the number of blocks before two signals are compared, the greater the error (introduced by the dispersion

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characteristics of the intervening blocks) between the zero and measurement channels.

The subtraction is made by a quadruple operational amplifier (LM324), which together with another LM324 also provides the analogue filtering and amplification required to bring the measurement and zero signals to a suitable level.

The filtering (identical for the two channels) is implemented by means of a first-order cell with gain of about 10, a Sallen and Key cell which gains 1, and a further first-order cell with adjustable gain between 1 and 10 after the differentiating circuit (with its gain of 10). Each cell is a low-pass filter with a cutoff frequency of about 20Hz; in this way a fourth-order low-pass filter with a cutoff frequency of about 15Hz is obtained.

For each channel, between the detector and the filter, a 1MΩ resistor is added to block the bias current coming from the amplifier input. After the differentiation circuit, PIC16F876A acquires and digitises the analogue signal, for subsequent transmission to a PC.

Hence, T [K] is the scene's temperature (human body or wall) seen by the antenna, and $k=1.38\times10^{-23}$ J/K is the Boltzmann constant. For a total-power radiometer, the available total power P at the receiver input is given by the Nyquist equation:

$$P = k(\eta T + T_R)B\ [W] \qquad (4)$$

and does not depend on the antenna's gain; the difference between the power received by the measurement channel in absence of a person

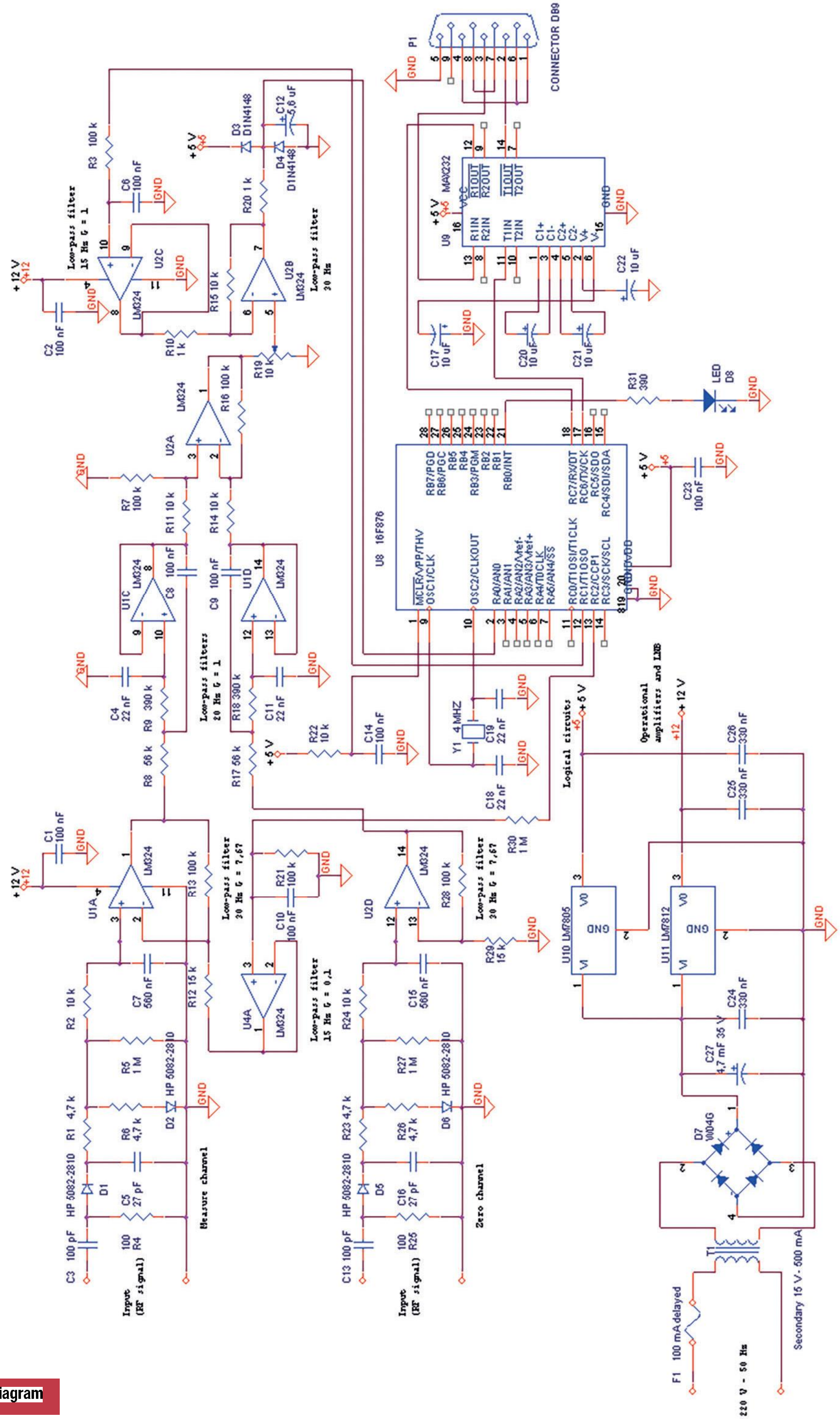

Figure 7: Circuit diagram

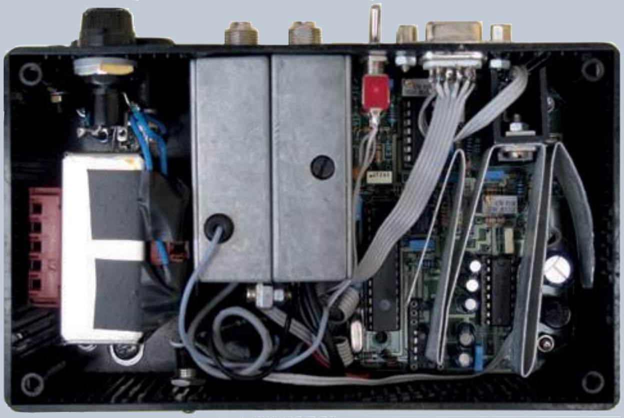

Figure 8: The equipment

Figure 9: The exhibit

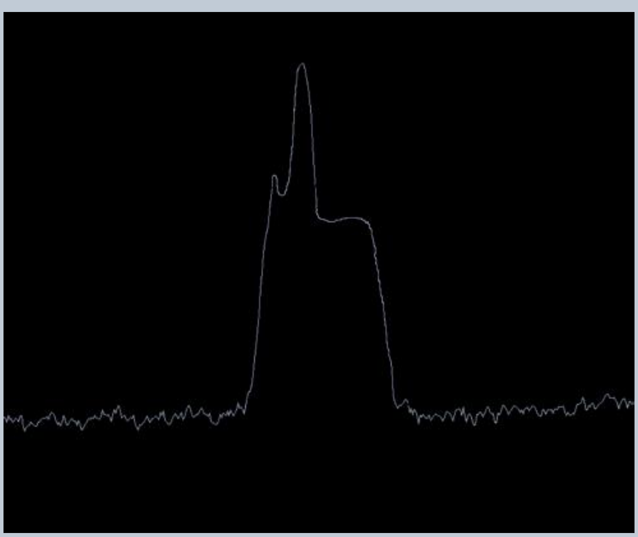

Figure 10: The monitor's display when a person moves in front of the antenna

(where there is a parabolic mirror) compared to that received by the zero channel (without the parabolic mirror) only due to η. Thus, the zero channel's gain is similar to that of the measurement channel.

Even in this case there are residual drifts, mainly due to unavoidable differences between the gains of the measurement and zero channels, be sure you provide for their active cancellation by means of a software integrator implemented with a PIC16F876A. In this case, the integration time may be much longer, in order to avoid falsified visualisations when a visitor remains in front of the paraboloid for a long time.

The +12V voltage required for the operational amplifiers and the LNB, and the +5V voltage required for the supply of the logic circuits, are obtained by means of the regulators 7812 and 7805, respectively. Figure 7 shows the overall circuit diagram, with Figure 8 showing the equipment.

System installation and tuning

During installation, tests were performed to optimise antenna placement for best system ΔT. It occurs:

1. without the subject; the antenna measures the lowest noise power. This will happen if in the absence of interfering signals the antenna "sees" a wall at the lowest temperature (in the presence of interference, minimum noise power could be achieved for antenna orientations other than toward the lowest temperature wall);
2. with the subject; the antenna measures the highest noise power. This will happen when the subject occupies the largest part of the antenna beam, within a few meters of the antenna.

The output of the measurement channel's line amplifier was connected to a Wavetek 1034A bolometer, with the zero channel's input connected to ground. Then the output signal was measured in function of the antenna placement and in the presence/absence of a person in front of the paraboloid. It was found that:

- Condition 1 is verified placing the antenna at about 3m above the floor pointed downwards obliquely toward the floor;
- Condition 2 is verified by pointing the antenna toward the area of the floor where it is expected a person to pass.

The LNB of the zero channel was placed near the paraboloid, so its wide beam (about 60°) always intercepts only the ceiling. Figure 9 shows the exhibit.

In the tuning stage, the two line amplifiers' gains were trimmed to be as equal as possible. Potentiometer R19 was adjusted so the variability range of the DC voltage at the processing input was within its working range (0-5V). Figure 10 shows the typical signal when a person moves in front of the antenna.

Double-receiver benefits

Compared with a single receiver, this double receiver still exhibits drifts that must be cancelled. In this case, however, the integration time of the offset circuit can be much longer, to prevent falsified visualisations when a visitor stays in front of the paraboloid for a long time or, as frequently happens, large groups of visitors crowd the area around the exhibit. These quick variations of the ambient temperature are very well compensated. EW