W-Band Direct Detection Radiometer Model

Mikuláš Šostronek, Zděnek Matoušek, Bohuslav Lakota, Miroslav Matejček
Dept. of Electronics
Armed Forces Academy of gen. M. R. Štefánik
Liptovský Mikuláš, Slovakia
mikulas.sostronek@aos.sk

Abstract **– This paper deals with evaluation and simulation of direct detection radiometer, which operates in the W-frequency band. Radiometers can be used in wide range applications in industry, military and security as well. One of the possible applications where the radiometers can be used is scanning of concealed dangerous objects. Main part of the article deals with the theoretical analysis of the basic total power radiometer parameters and their evaluation. Subsequently, the outcomes of the analysis are applied in design of radiometer model in Matlab® Simulink. In conclusion, the achieved results from experimental measurements are compared with calculated and simulated.**

Keywords- Radiometer simulation, Simulink, radiometer model.

I. INTRODUCTION

Nowadays, radiometers are widely used in security applications for detection of concealed weapons. By now, this task has been done by metal detectors; however with the invention of new weapons as ceramic knives or different kind of explosives this method can be hardly used.

Generally, the radiometer is a very sensitive RF receiver, which is intended for measuring of noise power that is emitted or reflected from surroundings. Inside the radiometer, this noise power is expressed by equivalent noise temperature named as a brightness temperature measured in kelvin. For this reason, it is necessary to calibrate the radiometer during the measuring and as a source of calibration signal the equivalent temperature of well-matched load at RF frequencies is often used [1]. This calibration temperature is compared with an antenna brightness temperature of scanned object and the contrast is evaluated. Very first radiometers, called as total power radiometers (TPR), were designed in 1960 and their primary utilization was at radio astronomy area. They were designed as analogue receivers with very high sensitivity (about 0.5 up to 1K) and from the design point of view with very simple scheme. Their significant issue was a large gain instability that brought not always usable results.

The later radiometer designs, such as Dicke radiometer, noise injected radiometer, etc. brought a better gain stability. However, these radiometers have relatively very complicated design with lover sensitivity compared to TPR. The rapid development in microwave technology has brought new low noise amplifiers with low noise that are more stable. The possibility to detect radiometric signal directly at the front end without the necessity of down convertors contributes to improve stability of radiometers, too.

II. THEORETICAL ASSUMPTION

The values of radiometer parameters limit its practical utilization and directly affect results of radiometer measurements. The basic parameters of radiometers are:

- noise figure;
- sensitivity;
- gain stability;
- absolute accuracy.

In the real life, the radiometer generates its own noise. The noise figure (NF) express how many times is the output noise of radiometer greater than its input noise caused by its own noise. Because the radiometer consists of microwave components cascade, its NF can be evaluated by Friise equation [3]

$$NF = F_1 + \frac{F_2 - 1}{G_1} + \frac{F_3 - 1}{G_1 G_2} + \ldots + \frac{F_n - 1}{G_1 G_2 \ldots G_{n-1}}, \quad (1)$$

where F_n is a noise figure of n-th radiometer component and G_n is a gain of n-th radiometer component. From (1) implies that the main part of overall NF is caused by the first stage of radiometer which is Low Noise Amplifier (LNA). The noise figure can be then calculated based on the following equation which expresses an equivalent noise temperature of radiometer T_N

$$T_N = 290(NF - 1) \quad [\mathrm{K}]. \quad (2)$$

This random noise is added to the antenna noise temperature T_A and cannot be separated during the further processing. The noise uncertainty of radiometer ΔT is defined as an ability to distinguish two noise temperatures with sufficient quality and it is given by [1], [2]

$$\Delta T_N = \frac{T_R + T_N}{\sqrt{B\tau}} \quad [\mathrm{K}], \quad (3)$$

where T_R is a reference temperature of calibration load in kelvins, T_N is a noise temperature of radiometer in kelvins, B is a radiometer bandwidth in hertz and τ is an integration time in seconds.

The output noise power of radiometer is defined by [1]

$$P = kBG(T_A + T_N) \quad [\mathrm{W}], \quad (4)$$

ISBN 978-80-261-0386-8, © University of West Bohemia, 2015

where k is a Boltzmann constant (1.38 x 10^{-23} J/K), G is overall gain of radiometer (included antenna gain) and T_A is a noise temperature of antenna.

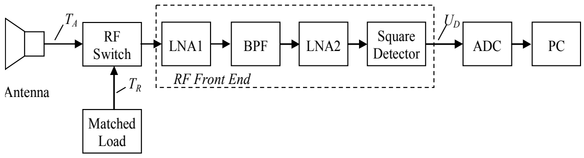

Figure 1. Measuring block diagram.

If the values of B, G and T_N are constants, there is no significant problem with radiometer stability. In ideal circumstances, the output noise of radiometer is a function of antenna noise temperature T_A. Practical realizations of radiometers prove that a constant radiometer bandwidth is achieved by usage of high quality passive microwave components. One of the main issues which the real radiometric measurements struggle is stabilization an overall gain G and its noise temperature T_N which represents properties of active components. The serious error in radiometric measurements arises due to large gain instability that influences the measurement outcomes. In general, this error arises in all radiometer amplifiers and is given by [4]

$$\Delta T_G = (T_A + T_N)\frac{\Delta G}{G} \quad \text{[K]}, \qquad (5)$$

where ΔG is an effective value (rms) of a power gain variation (AC component).

III. Concept of Radiometer

Based on above listed assumptions and calculations, experimental system of total power radiometer in millimeter wave band has been designed. A practical realization of the W-band radiometric module is based on the Farran Technology Ltd. direct detection radiometric module and it is shown at Fig. 2.

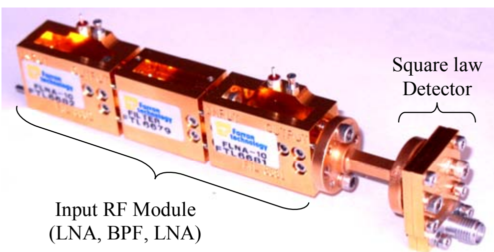

Figure 2. W-band direct detection radiometric module by Farran Technology, Ltd.

RF front end part of radiometer (Fig. 1) is intended primary for amplification and filtration of input noise power from the antenna (measured object). It consists of two LNAs and a microwave band pass filter (Fig. 2). Parameters of these circuits are summarized in Tab. 1 [5].

In Tab. I, the overall noise figure of RF front end is computed from (1). On its basis, the noise temperature of the radiometer was evaluated based on (2) and its value is T_N = 276,254 K. Microwave pass band filter has a bandwidth B = 11.7 GHz centered at 94 GHz. Values of the noise power at the radiometer RF front end part was evaluated based on the (4) and it is in range from P_{MIN} = 5.4826 µW to P_{MAX} = 2.429 µW for antenna noise temperature T_A in range from 0 to 350 kelvins.

TABLE I. Radiometer RF Frond end parameters.

Circuit	Type	NF [dB]	NF [-]	Gain [dB]
1. LNA	FTL 6681	2.903	1.95	27.348
2. LNA	FTL 6682	2.93	1.96	26.679
BPF	FTL 6679	0.9	1.23	-0.9
RF Front End	---	2.907	1.953	53.127

According to (4) the value of P_{IK}, which corresponds to antenna temperature change by 1 kelvin, was calculated. The dynamic range of the output noise power ΔP is given by difference P_{MAX} and P_{MIN} it is equal to 11.61 micro watts.

The quadrature detector of radiometer (quadrature diode detector FTL 6680) serves as sensing low frequency component of noise power at the radiometer output and it has sensitivity equal to S = 2.2 mV/µW [5]. The detector output voltage for given input noise power P_{IN} is given by equation

$$U_D = S_D \, P_{IN[\mu W]} \quad \text{[mV]}, \qquad (6)$$

where $P_{IN[}$ is a noise power at the input of quadrature detector in micro watt.

The calculated values of output noise power of RF front end and output voltage of quadrature detector are summarized in Tab. II.

TABLE II. Computed output voltages of quadrature detector.

	Output noise power from RF Front End [µW]	Output voltage of quadrature detector [mV]
1.	P_{MIN} = 9.1637	U_{DMIN} = 20.16
2.	P_{296K} = 18.9825	U_{D296K}= 41.7615
3.	P_{MAX} = 20.0774	U_{DMAX} = 44.1703
4.	ΔP = 11.61	ΔU_D = 24.0103
5.	P_{IK} = 0.03317	U_{D1K} = 72.976x10^{-3}

For experimental measurements, the USB-1608FS data acquisition device from Measurement Computing was used. It consists of 16-bit ADC [6]. For 4V (±2V) range, its absolute accuracy is 61.035 µV, which means that theoretical achievable resolution of the radiometer is $\Delta T \approx$ 0.836 kelvin. Initial experiments were focused on evaluation of the quadrature detector output signal in order to get information about its characteristics. For the reason that the radiometer measurements are temperature dependent, the measurements were done in 50 minute time frame and consequently upper mentioned dependence was evaluated at reference matched load with temperature of 296 kelvins. Time period for starting of AD conversion was set to 60 seconds. This time interval was sufficient for obtaining the relevant data and further processing. When conversion starts, 1024 samples of output signal from quadrature detector were collected during approximately 20 milliseconds interval and a result value was expressed as a mean (average) of these samples. The experimental measuring site is at Fig. 3.

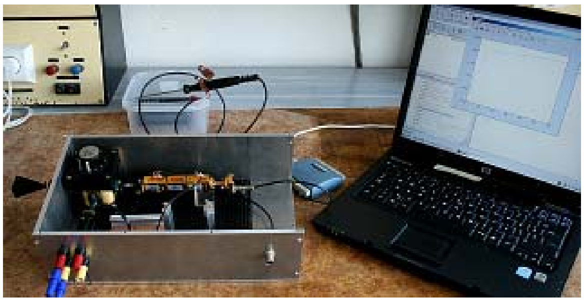

Figure 3. Experimental measuring site.

IV. Radiometer model in Matlab® Simulink

According to previous text we have simulated direct detection radiometric module in Matlab® Simulink. A simulation time was set at 3000 seconds, a solver is set to ode45 (Dormand-Prince) and rest of settings were set automatically by Simulink.

After warm-up process the output voltage of detector linearly increases, which is simulated by ideal integrator with transfer function

$$G_2(s) = \frac{1\times 10^{-5}}{s}.$$

Its effect is evident after 250 second transport delay which is expressed by transfer function

$$G_3(s) = e^{-sT} = e^{-s250}$$

where T = 250 sec is delay time. $G_3(s)$ can be approximated by Maclaurin series into [7]

$$G_3(s) = \frac{-T/2s+1}{T/2s+1} = \frac{-250/2s+1}{250/2s+1}.$$

All time constants have been evaluated experimentally according to output voltage of direct detector radiometer from Fig. 5.

As one can see from simulation results in Fig. 5 the output of the radiometer after warm up time is relatively good predictable. The output voltage of the radiometer according to computed values in Table 2 is well fitted as we can see from the box Quadrature

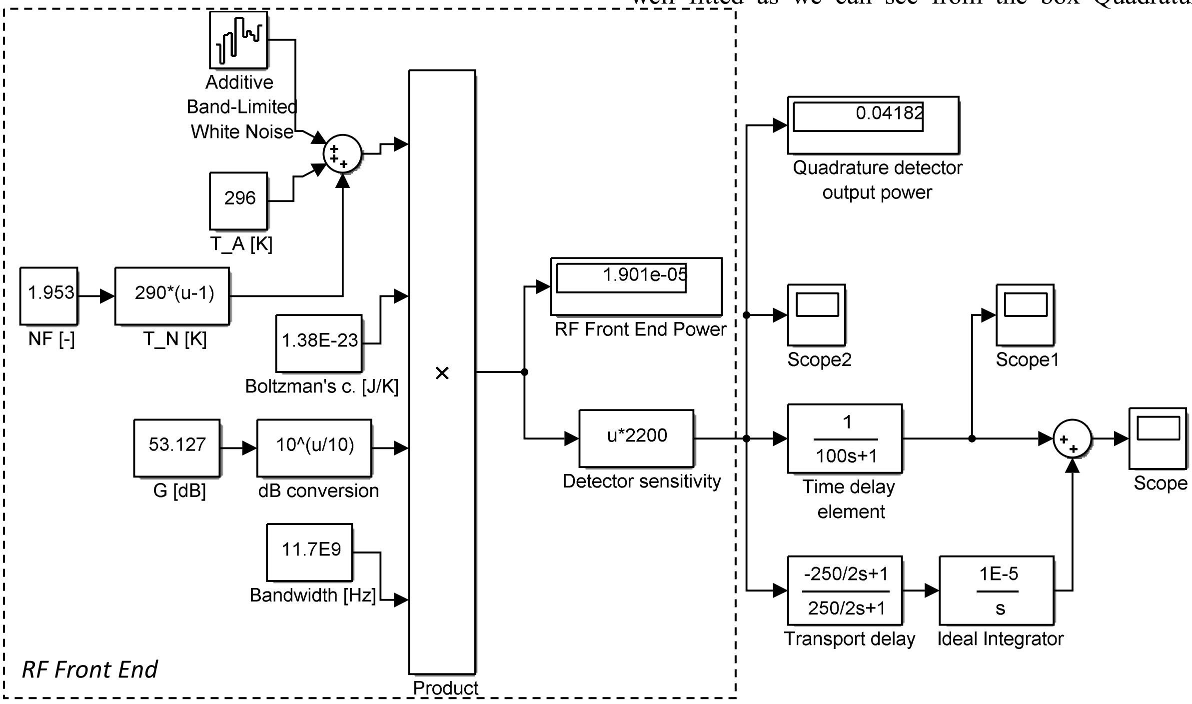

Figure 4. Model of direct detection radiometric module.

Fig. 4 shows a model of above mentioned radiometric module in W-frequency band. Diagram in dashed box (on the left side of Fig. 4) is model of radiometer RF front end designed according to (2), (4) and (6). At the right side of Fig. 4 there is a diagram that represents warming-up process of radiometer after its connection to power supply and next behavior after stabilization of detector output voltage U_D. The warming-up process is simulated by time delay element with a transfer function

$$G_I(s) = \frac{1}{100s+1}$$

from Simulink library. The time constant was set at 100 seconds for our case and it depends on time when warm-up process of radiometer ends.

detector output power in Figure 4 (state at the end of simulation) and from graph at Figure 5, too.

An absolute error of simulation can be computed according to

$$\Delta = U_{D296K\_Sim} - U_{D296K}$$

A percentage relative error of simulation is then given by

$$\delta = \frac{\Delta}{U_{D296K}}.100 \quad [\%]$$

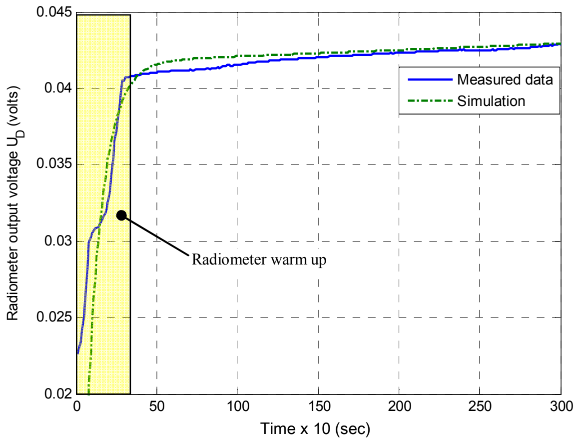

Figure 5. Measured and simulated data from radiometer output.

A final graph of percentage relative error is shown at Fig. 6. As one can see from the picture an overall error of simulation after radiometer warm-up time is less than 2 %.

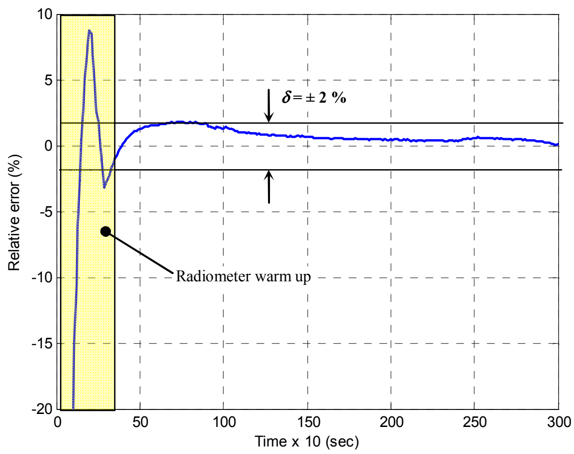

Figure 6. Percentage relative error of simulation.

V. Conclusion

Few years ago the TPR radiometers were very unstable because of the amplifiers gain instability in the front end of radiometer [1]. One of the solutions was to design a radiometer as Dicke radiometer. This type of radiometer has better stability but twice as worse sensitivity as TPR radiometers. Nowadays a stability of modern total power radiometers is relatively good thanks to new low noise amplifiers based on InP HEMT MMIC devices with low noise and a direct detection at the RF front end of the radiometer [8]. As was mentioned above the output voltage of that radiometer after warm-up time is well predictable in 2 % error in 45 minute time span. There is no necessity to often measure the temperature of a calibration load to improve stability of radiometer output.

In the next research there will be designed a more complex radiometer model that will allow advanced simulations of overall device behavior to find its optimal operation as it is recommended for these more complex research projects [9].

Acknowledgment

This work was partially supported by project SEMPO-38-1/2014-OMOS – Sensors and Sensor Systems in Military and Security Applications.

References

[1] N. Skou, D. Le Vine, "Microwave Radiometer Systems. Design and Analysis", Artech House, Norwood, 2006, ISBN: 1-58053-974-2G.

[2] D. Pozar, "Microwave Engineering", 4-th Ed. McGraw- Hill, New York 2011

[3] B. R. Mafhaza, "Introduction to radar analysis", CRC Press, Boca Raton, 2006, ISBN: 0-8493-1879-3.

[4] F. T. Ulaby, R. K. Moore, A. K. Fung, „Microwave remote sensing: Active and Passive. Volume I, Microwave Remote Sensing, Fundamentals and Radiometry“. Addison-Wesley, Reading, Mass, 1981.

[5] Farran Technology Ltd., "W-band Direct Detection Module With 2 x LNA, 1 x Filter, 1 x Detector", Job No: 1942 Elsinco, datasheet, pp. 1-5, January 2007.

[6] M. Šostronek, Zd. Matoušek, et al., "Experimental verification of radiometer properties", Proceedings on New Trends in Signal Processing 2012, NTSP 2012, Tatranské Zruby, May 2012, pp. 148-153.

[7] R. C. Dorf, R. H. Bishop, "Modern Control Systems" 12-th Edition, Pearson, New Jersey, 2010, ISBN-13: 978-0136024583.

[8] Essen, H. et al.: "Concealed Weapon Detection with Active and Passive Millimeterwave Sensors, Two Approaches" [online 02. 06. 2015] http://duepublico.uni-duisburg-essen.de/servlets/DerivateServlet/Derivate-14694/Final_Papers/GM0004-F.pdf.

[9] Lacko, B.: "Modeling and simulation in project". Preceedings of wokshop "MSP 2001 - Modeling a simulation of projects". TU of Brno, 2001, p. 5 - 20, ISBN 80-214-1734-X. (In Czech).