REDUCTION OF SYSTEMATIC ERRORS IN DIAGNOSTIC RECEIVERS THROUGH THE USE OF BALANCED DICKE-SWITCHING AND Y-FACTOR NOISE CALIBRATIONS*

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Abstract

Receivers designed for diagnostic applications range from those having moderate sensitivity to those possessing large dynamic range. Digital receivers have a dynamic range which is a function of the number of bits represented by the ADC and subsequent processing. If some of this range is sacrificed for extreme sensitivity, noise power can then be used to perform two-point load calibrations. Since load temperatures can be precisely determined, the receiver can be quickly and accurately characterized; minute changes in system gain can then be detected, and systematic errors corrected. In addition, using receiver pairs in a balanced approach to measure BPM X+, X-, Y+, and Y- electrodes reduces systematic offset errors from non-identical system gains. This paper describes and demonstrates a balanced BPM-style diagnostic receiver, employing Dicke-switching to establish and maintain real-time system calibration. Benefits of such a receiver include wide bandwidth, solid absolute accuracy, improved position accuracy, and phase-sensitive measurements. System description, static and dynamic modelling, and measurement data are presented.

INTRODUCTION

Diagnostic receiver calibration usually depends on injection of a stabilized RF test source. Reference oscillator amplitude and receiver gain variations are induced by voltage changes, as well as ambient temperature. As a result, stabilization of less than 0.5 dB is difficult and impractical. An appeal to radio astronomy techniques presented by Dicke in 1946 demonstrates that careful measurement of noise can provide the necessary calibration information, provided the receiver is sensitive enough to distinguish thermal noise sources [1].

DICKE-CLASS RECEIVERS

Graham's Receiver Architecture

Switched-electrode electronic (SEE) receivers employ a single receiver front-end, preceded by an RF multiplexer [2]. Gain fluctuations are experienced by all channels, effectively cancelling their effects. However, output bandwidth is sacrificed in such a scheme, since data is lost while neighboring channels are selected. In addition, effective receiver sensitivity is reduced by the number of channels [3].

The appearance of dual-channel, direct-digital downconverter ICs (DDCs), such as the Analog Devices AD6655, present an attractive means of employing balanced architectures [4]. A Graham receiver is an improvement for the Dicke-class of radiometers, whereby two parallel channels are alternately connected to thermal noise sources and an antenna [5]. The outputs are summed, and demultiplexed at the rate of antenna switching, as demonstrated in Fig. 1. The noise power serves as a basis for determining signal power. Since the received signal is always sampled, sensitivity is improved, and output bandwidth is increased [3].

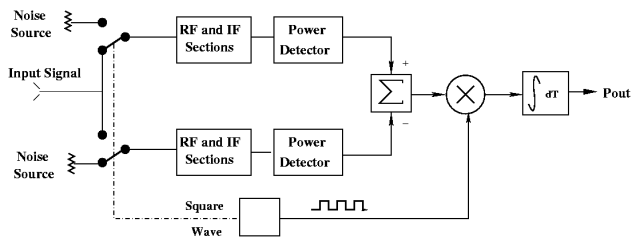

Figure 1: Graham's version of Dicke-switched receiver, adaptable to BPM measurements. Signal and noise are continually compared to monitor gain fluctuations.

This approach can be applied to a difference-over-sum BPM in order to minimize position sensitivity to gain fluctuations, by alternately switching X_a and X_b streams through each channel, having gains G_a and G_b, :

$$X_1 = \frac{G_a X_a - G_b X_b}{G_a X_a + G_b X_b}$$

$$X_2 = \frac{G_b X_a - G_a X_b}{G_b X_a + G_a X_b}$$

Now, let $\delta = Ga/Gb$ represent the gain fluctuations, with respect to Channel A. Then, the simple average of the above terms yields:

$$X_{pos} = \frac{(X_a + X_b)(X_a - X_b)}{X_a^2 + (\delta + \frac{1}{\delta}) X_a X_b + X_b^2}$$

In this manner, position errors are reduced by more than an order of magnitude for large gain fluctuations, and

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further suppressed for $X_a / X_b \approx 1$, or when the beam is nearly boresighted.

A 4-channel diagnostic receiver using AD6655 DDCs, an Altera Cyclone 3 FPGA for DSP firmware, and a PC-104 serving as an IOC was built for development, and configured as shown in Fig. 2. Simple switching was performed on simulated 1uA beam, with normalized offset of 0.5. The results shown in Fig. 3 agree well with predicted performance.

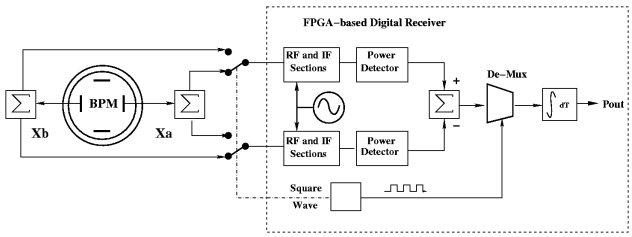

Figure 2: Block diagram of development diagnostic receiver used in balanced configuration. FPGA-based DSP algorithms facilitate a flexible test platform.

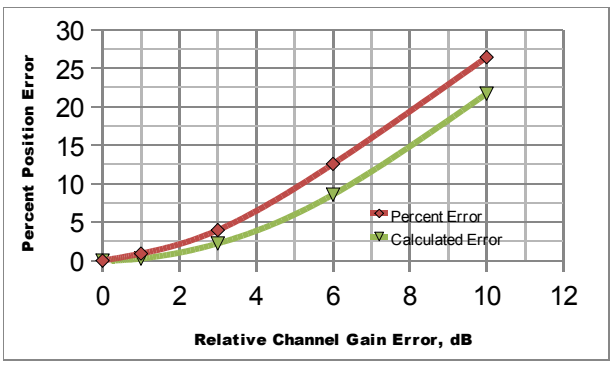

Figure 3: Percent position error vs. relative channel gain imbalance, demonstrating improvement to sensitivity by employing balanced Dicke switching. A simulated, normalized position of 0.5 was used as a basis.

Y-FACTOR NOISE CALIBRATION

Incoherent white noise power is emitted as a result of Blackbody Radiation, and is a function of ambient temperature and receiver bandwidth, described by [3]:

$$Pn = KTB$$

where :

K = Boltzmann's Constant of 1.38×10^{-23} JK^{-1}

T = Physical temperature, K

B = receiver bandwidth, Hz.

This useful relationship is the basis by which receiver noise figure measurements are made [6]. In addition, noise powers can be used to calibrate Dicke radiometer receivers, as long as the effective noise source temperatures are known [3]. Typically, loads representing a hot and cold temperature are alternately connected and used to determine the system gain. Since temperature is a relatively easy measurement to make, system gain can be measured with extreme accuracy. In addition, calibrated noise diode sources are available which represent physical temperatures of up to 10^6 K, and low temperature coefficients of 0.01 dB/K [7]. The measurement configuration is shown in Fig. 4. T_c is generally a 50 Ohm load, at 300 K. T_h is a noise source with effective noise temperature at 365,000 K, representing 31 dB excess noise ratio (ENR).

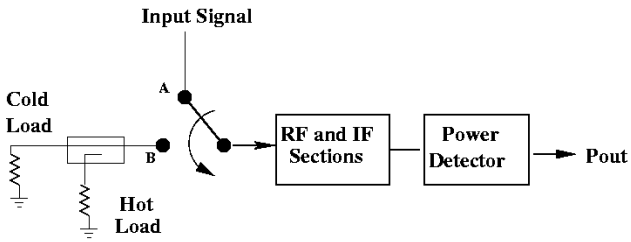

Figure 4: Block diagram showing the alternation between signal, cold load , and "hot load" noise source for comparison with thermal-induced white noise.

With the antenna switch in the normal receive position, the desired signal power is detected, resulting in an effective system composite noise temperature, T_{sig}. When the cold load is selected (noise source is off), noise power is recorded. Activation of the noise source results in an effective hot load measurement. These are represented by:

$$P_{signal} = K(T_{ant} + T_{rx})B$$

$$P_{cold} = K(T_{cold} + T_{rx})B$$

$$P_{hot} = K(T_{hot} + T_{rx})B$$

Power ratios can now be created, and are given by:

$$Y_1 = \frac{T_{cold} + T_{rx}}{T_{ant} + T_{rx}} = \frac{P_{cold}}{P_{signal}}$$

and

$$Y_2 = \frac{T_{hot} + T_{rx}}{T_{ant} + T_{rx}} = \frac{P_{hot}}{P_{signal}}$$

Subsequently, system noise temperature, and most importantly, receiver noise temperature can be calculated by:

$$T_{sys} = (T_{ant} + T_{rx}) = \frac{T_{hot} - T_{cold}}{Y_2 - Y_1}$$

$$T_{rx} = Y_1 T_{sys} - T_{cold}$$

If a directional coupler is used for the hot load, as shown, instead of a switch, the relationship between receiver temperature and noise factor, K_1, is [3]:

$$T_{rx} = \frac{\frac{1}{L_d}(T_{hot} - K_1 T_{cold}) + (1 - \frac{1}{L_d})(T_{hot} - K_1 T_{cold})}{K_1 - 1}$$

where L_d is the coupler attenuation (linear units).

K_1 is ultimately the receiver channel gain, and can be measured, tracked, and applied as needed. In operation, the cold load measurement is easily obtained by momentarily shifting the receiver's local oscillator frequency to an empty RF channel. Use of a directional coupler for injection of the hot noise source permits a single input connection and preserves the input impedance match, which can otherwise affect the measurement.

Receiver bandwidth needs to be wide enough to let in reasonable power levels. A pre-detector BW of 100 kHz is typical, while post-detection integration limits the output BW to tens of Hz, thus reducing standard deviation levels. The 4-channel development receiver was again used to compare hot and cold noise sources of 300 K and 365,000K, respectively, with 1 MHz input BW, and 1 ms integration interval. The on-board thermometer recorded 51C, or 324 K, ultimately yielding a noise factor of 7.9. .

CONCLUSION

Adaptation of a Graham/Dicke-switched receiver has been demonstrated. In addition, Y-factor measurements are easily incorporated into the switching process, to provide real-time calibration. The receiver must have a noise figure low enough to distinguish ambient noise. Commercial noise sources are available which can be applied to most systems with proper attenuation and coupling,. On-board thermometry provides precise measurement of cold load temperatures, and can also be used to provide data correction through dead-reckoning.

Finally, powerful FPGA platforms support extensive calculations and DSP algorithms, facilitating near-real time signal processing and self-calibration and correction.

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